55 LAND MANAGEMENT HANDBOOK

Snow Avalanche

MANAGEMENT IN FORESTED TERRAIN

Snow Avalanche MANAGEMENT IN FORESTED TERRAIN

BRITISH COLUMBIA
Ministry of Forests
Forest Science Program

103-06820/

Snow Avalanche

MANAGEMENT IN FORESTED TERRAIN

Peter Weir

BRITISH COLUMBIA
Ministry of Forests
Forest Science Program

The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the Government of British Columbia of any product or service to the exclusion of any others that may also be suitable. Contents of this report are presented as information only. Funding assistance does not imply endorsement of any statements or information contained herein by the Government of British Columbia.

National Library of Canada Cataloguing in Publication Data

Weir, Peter.

Snow avalanche management in forested terrain

(Land management handbook ; 55)

Includes bibliographical references: p.

ISBN 0-7726-4881-6

1. Avalanches - Control. 2. Avalanches - British Columbia - Control. 3. Forests and forestry - Environmental aspects - British Columbia. 4. Forest management - British Columbia. I. British Columbia. Ministry of Forests. Research Branch. II. Series.

TA714.W44 2002 551.57'848 C2002-960254-8

Citation

Weir, Peter. 2002. Snow avalanche management in forested terrain. Res. Br., B.C. Min.For., Victoria, B.C. Land Manage. Handb. No. 55. www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh55.htm

For more information on Forest Science Program publications, visit our web site at www.for.gov.bc.ca/hfd/pubs/index.htm

© 2002 Province of British Columbia

When using information from this or any Forest Science Program report, please cite fully and correctly.

ABSTRACT

Snow avalanches are a common phenomenon in most mountain ranges of British Columbia and forest damage is a natural occurrence. Forest harvesting on steep slopes in areas of high snow supply can create new avalanche start zones. Snow avalanches starting in recently harvested areas can damage new plantations, destroy downslope forest resources, and lead to soil loss and site degradation. Snow avalanches can be triggered by forest workers or winter recreationists in steep cutblocks; that is, in areas that were not prone to avalanching prior to harvest.

This handbook addresses snow and avalanche phenomena in a forestry setting and presents a risk assessment procedure suitable for incorporation in the terrain stability field assessment process. The handbook outlines harvest design and silvicultural strategies to reduce the risk of avalanche damage resulting from forest harvesting. Strategies for managing avalanche risks in winter are presented. An extensive bibliography is included, along with links to relevant publications, data sources, and resources available on the internet.

PREFACE

Recent Forest Renewal BC-funded research undertaken at the University of British Columbia shows that there are approximately 10 000 clearcut forest blocks in British Columbia that have been significantly affected by avalanching. The majority of these cutblocks have been affected by natural snow avalanches running in from above, but 10% of the cutblocks surveyed were found to have generated avalanches that had damaged new plantations within the blocks or forest resources downslope. Clearcut forest harvesting on steep terrain, particularly in areas of high snow supply (in coastal British Columbia and Vancouver Island mountains where the mean annual maximum snow accumulation exceeds 1000 mm water equivalent and in the interior mountain ranges where mean annual maximum snow accumulation exceeds 700 mm water equivalent) can create new avalanche start zones.

On January 20, 2000, a group of 26 forest and heliski industry representatives, provincial government officials, and consultants with expertise in snow avalanches, forestry, and terrain mapping convened in Revelstoke, B.C. to identify issues to be addressed in a Land Management Handbook proposed by the British Columbia Ministry of Forests. The resulting draft handbook, *Forest Management of Snow-Avalanche-Prone Terrain*, was circulated to interested parties and then debated at an open workshop attended by 36 people in Revelstoke on March 16, 2000. The document was amended following receipt of written submissions.

Key issues identified and discussed at the two meetings included:

(1) The need to establish whether snow avalanches represent a significant threat to downslope forest resources or restocked cutblocks. While the avalanche phenomenon is not regarded as a province-wide issue for the forestry sector, the hazard is considered significant on steep terrain in areas of high snow supply and in regions where the climate is conducive to development of weak layers in the snowpack. Also pertinent to this discussion was the need to define what degree of resource loss attributable to snow avalanches is tolerable.

(2) The need to provide guidance for the scheduling of winter operations to avoid unacceptable risks and to establish appropriate avalanche safety programs where winter harvesting may expose workers to avalanche hazards. It was noted that the prescription of "winter cable harvest," a recommendation commonly advanced to minimize soil or stream disturbance, could markedly increase the avalanche hazard faced by workers.

Also recognized was the need to tailor the nature and scope of avalanche safety and control programs to the avalanche environment. Current industry programs and response to the avalanche hazard are quite varied.

(3) The need to assign responsibility for public safety should forest harvesting expose downslope residents, facilities, utilities, or transport corridors to significantly increased involuntary risk. A subsidiary issue discussed was the potential for forest harvesting to elevate the avalanche risk faced by winter recreationists or commercial operators travelling on forest roads passing through steep cutblocks that may be subject to snow avalanches.

This handbook, representing the culmination of all the workshops, discussions, and expert input, is primarily intended for foresters, forest technicians, engineers and engineering technicians, geoscientists, harvest supervisors, and others responsible for managing forests and risk in avalanche-prone terrain. It can be used in identifying avalanche hazards and in planning silvicultural operations so that cutblock configuration and harvesting systems minimize the avalanche hazard. It also identifies knowledge gaps, setting out areas for future research and method development.

Highlighted in the handbook are issues to be considered by managers and avalanche technicians who deal with both worker and public safety. As well, resource protection issues are stressed for the benefit of avalanche technicians who may be called on to assess snow stability and, where avalanche danger exists, to perhaps mitigate the danger by artificially triggering unstable snow with explosives. Forest operations without in-house avalanche management capability will find guidance as to when specialists should be called in to undertake snow stability or avalanche assessments. Overall, the handbook emphasizes practical aspects of the subject matter, summarizes the present state of knowledge, and identifies the best industry practice. Some operators working in avalanche-prone terrain in British Columbia have developed avalanche risk management programs that demonstrate it is possible to proactively "manage with residual risk." This involves a subtle, but important, difference from more conservative risk avoidance strategies.

There are no known controlled trials of cutblock design in British Columbia that clearly point to optimum strategies to minimize the avalanche hazard. Avalanching is seldom general or widespread, but it can occur repeatedly in some cutblocks. Examples of cutblocks that

have produced or endured destructive avalanches are presented in the handbook to illustrate avalanche-prone configurations. Observations of adjacent cutblocks harvested in areas of high snow supply indicate subtle topographic features, the presence of road fillslopes, and surface roughness elements that may alter avalanche susceptibility.

The heliski industry, in partnership with forest companies, has demonstrated that recreational and commercial opportunities can be created by forest harvesting that avoids using avalanche-prone cutblock configurations. At the same time, it is known that commercial heliski, snowcat, and wilderness skiing opportunities can be adversely affected by the creation of large clearcuts above prime recreational terrain.

In 1996, the B.C. Ministry of Forests commissioned a review of the international snow and avalanche literature related to forestry practices in snow avalanche terrain. Key findings and case studies from this review are cited here. In North America, research into avalanche issues related to operational forestry is a very young science. Forest Renewal BC funded a 4-year research program at the University of British Columbia to investigate snow avalanche activity in the province's forests and develop a decision support system for forested and harvested terrain. Research outcomes, expected by 2003, will update the guidance in this handbook. Given the large avalanche observation databases that exist in British Columbia, it is anticipated that avalanche assessment procedures will evolve to become the most quantitative of all geotechnical assessments undertaken in the forest sector.

Where Forest Practices Code Regulations and Occupational Health and Safety Regulations are mentioned, they are current in British Columbia as of March 2001 unless otherwise noted. The names of the province's ministries and agencies are also those as of March 2001.

Each photographer identified retains the copyright of the photographs in this text. See Photo Credit section starting on page 181.

ACKNOWLEDGEMENTS

The encouragement and support of the following people and organizations was greatly appreciated:

- Dr. D. McClung (Chair, Avalanche Research Group, University of British Columbia)
- S. Chatwin, P. Geo., Forest Practices Board, who originated this project.
- Contributors and reviewers of the preliminary draft, including: B. Allen; F. Baumann, P. Eng.; J. Bay; M. Deschenes, E.I.T.; A. Freeland; Dr. B. Jamieson, P. Eng.; Dr. P. Jordan, P. Geo.; D. Kelly, L.L.P. Geo.; P. Kimmel; H. Krawczyk; K. Marr; B. Runciman, R.P. Bio. and S. Walker
- L. Redfern, R.P.F. and Crestbrook Forest Industries
- Staff of the B.C. Ministry of Transportation and Highways Snow Avalanche Program, Victoria
- D. Rowe, Workers' Compensation Board (WCB), Prevention Division, Northern Region and other WCB representatives
- Staff of the B.C. Ministry of Forests, Nelson Forest Region and Columbia Forest District
- Participants attending the Revelstoke project initiation meeting and subsequent workshop
- The Canadian Avalanche Association technical committee and the Division of Engineers and Geoscientists in the Forestry Sector guidelines committee members who reviewed the final draft of this handbook.

ABOUT THE AUTHOR

Peter Weir, P. Geo., M. IPENZ, is a geoscientist and avalanche specialist with over 20 years experience in the transportation and forestry sectors. He has worked in highway avalanche forecasting and control programs in Canada and New Zealand, and currently is a partner in a consulting company, Geoscience Solutions Group, which specializes in services to the forest industry. In 2001–02, he was chair of the Division of Engineers and Geoscientists in the Forest Sector of the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC).

CONTENTS

Abstract iii
Preface v
Acknowledgements viii
About the Author viii

1 Management of Snow Avalanche–prone Forest Terrain 1
1.1 Background 1
1.2 Avalanche Risk Management in British Columbia Forests 3
Avalanche Risk in Context 4

2 Snow and Avalanche Phenomena 7
2.1 Seasonal Snow 7
Snow Accumulation 8
Energy Exchanges over Snow 10
2.2 Avalanche Phenomena 11
Snow Avalanche Classification 11
Slab Failure 13
Snow Avalanche Path Nomenclature 14
Creep and Glide 17
Avalanche Size 18
Snow Supply 19
Avalanche Frequency 21
Avalanche Probability 24
2.3 Avalanche Dynamics 28
Avalanche Speed and Motion 28
2.4 Identification of Snow Avalanche Terrain 31
2.5 Runout Characteristics 33
2.6 Role of Forest in Avalanche Protection 34
2.7 Hydrological Effects 35
2.8 Ecological Significance 37
Grizzly Bear Habitat 38
Habitat Protection Guidelines 43

3 Avalanche Risk Assessment 45
3.1 Protection Forests 45
Avalanches in British Columbia Forests 47
3.2 Avalanche Risk Classification 48
Risk Assessment 48
Assessing Risk to Forest Cover 50
Assessing Risk above Transportation Corridors, Facilities, or Essential Resources 51
Consequence 52
Risk Management Strategies 53
Responsibility for Risk Management 55
3.3 Ownership of Risk in Forest Operations 56

3.4 **Logging above Highways** 57
3.5 **Avalanche Mapping** 62
Air Photo Interpretation 63
Field Checking 64
Avalanche Mapping for Land Use Planning 66
Map Use and Interpretation 74
3.6 **Documenting Existing Avalanche Paths** 75
3.7 **Runout Prediction** 75
Dynamics Modelling Approach 75
Probabilistic Modelling Approach 77
Statistical Concepts 80
3.8 **Impact Pressures** 82

4 Mitigation 85
4.1 **Harvest Design** 85
Slope Length 86
4.2 **Silvicultural Strategies** 91
Increasing Surface Roughness 91
Modification of Local Scale Climate 93
Retention of Timbered Margins Adjacent to Avalanche Runout .. 94
Species Vulnerability 94
4.3 **Effects of Harvesting on Heliski, Snowcat, and Wilderness Skiing Operations** 94
4.4 **Stream Crossing Location and Road Layout** 95

5 Managing Avalanche Risks in Winter 101
5.1 **Field Observations and Recording Systems** 101
5.2 **Class I Data: Avalanche Observations** 102
5.3 **Class II Data: Snowpack** 103
Snow Profile Interpretation 106
Numerical Avalanche Forecasting 108
5.4 **Class III Data: Weather Observations** 108
Permanent Weather Stations 111
5.5 **Mountain Weather Forecasting** 112
5.6 **Avalanche Control** 114
Passive and Active Control 114
Consider the Outcome 115
When, and When Not, to Trigger Avalanches 115
Consider the Runout, Consider the Consequences 117
Helicopter Bombing 117
5.7 **Winter Operations** 119
Harvesting Operations 119
Snowmobiles in Forest Operations 120
Removal of Avalanche Debris on Roads 121
5.8 **Avalanche Rescue** 122
Rescue Transceivers 122
Alternative Rescue Systems 126
Rescue Caches 126

Rescue Exercises 127
5.9 Information Exchanges and Avalanche Bulletins 127

6 Case Studies of Risk Assessment 129
6.1 Wardance Slope at Big Sky, Montana 129
6.2 Protection Role of Forests above the Coquihalla Highway, B.C. 130
6.3 Avalanche Triggered in Cutblock Kills Recreationist near Salmo, B.C. 131
6.4 Ranch Ridge, near Hills, B.C. 131
6.5 Airy Creek in the Slocan Valley, B.C. 132
6.6 Nagle Creek Cutblocks, near Mica Creek, B.C. 133
6.7 Avalanche in a Block with Active Logging, Southern Interior, B.C. 135
Day One – Accidental Triggering 135
Day Two – Equipment Damaged during Avalanche Control 137
Incident Review 139
Development of Safe Work Procedures for Snow Stability Assessment in Active Harvest Areas 139

APPENDICES
1 Occupational health and safety regulations 143
2 Safe forest operations in avalanche-prone terrain 145
3 Online resources and information sources 154
4 Avalanche site identification form 158
5 Avalanche assessment checklist 160
6 Snow stability rating system 162

Glossary 163
References 167
Photo Credits 181
Index 188

TABLES

1 Influence of forest cover on the climate parameters that affect snow stability 11
2 Snow avalanche types described according to release mechanism ... 12
3 Conversion of units used in measuring slope angle 16
4 Classification of snow avalanche size 19
5 Terminology used to describe frequency of mountain slope hazards ... 23
6 Encounter probability for various return period avalanches in given periods 25
7 Vegetative indicators of snow avalanche frequency 26
8 Ranking of avalanche start zone wind exposure 32
9 Differences in snow accumulation and stability between forest openings and closed canopy coniferous forest 35
10 a) Species whose habit includes snow avalanche–prone terrain by British Columbia biogeoclimatic zone 39
b) Key to biogeoclimatic units referenced in Table 10a 42
11 Estimate of avalanche likelihood from site-specific observations and analysis of climate data 50
12 Risk ratings for expected avalanche size and expected avalanche frequency for forest harvest resulting in damage to forest cover 51
13 Risk ratings for expected avalanche size and frequency for forest harvest when downslope transportation corridors, facilities, or essential resources may be affected 52
14 Examples of risk management strategies 53
15 Appropriate risk responses 54
16 Mapping methods that may be applicable for use in snow avalanche–prone terrain 60
17 Fraser Valley Regional District snow avalanche planning response .. 72
18 Avalanche runout summary statistics: mean values 79
19 Avalanche runout summary statistics: extremes 79
20 Relation between impact pressures and potential damage 82
21 Scale effects on snow accumulation 86
22 Basic snow grain classification 105
23 Snowpack hardness test 105
24 Typical observations of weather, snow, and avalanche data 110
25 First avalanche start zone: geometry and dimensions 137
26 Second avalanche start zone: geometry and dimensions 139

FIGURES

1 Significant forest damage caused by a snow avalanche at Ningunsaw Pass 5
2 Snow avalanches that run into cutblocks or onto roads on Duffey Lake Road near Lillooet 5
3 Resource loss in standing forest near Nagle Creek 6
4 Some forms of new snow 7
5 Coast Range snowpacks accumulate as a series of snow wedges truncated by melt at low elevations 9
6 Typical layering in a winter snowpack 9
7 Mountain barriers in southern British Columbia impinging on the prevailing synoptic-scale westerly circulation 9
8 Surface hoar 10
9 Loose snow avalanches start small but grow in mass as they move downslope 12
10 Failure surfaces in a slab avalanche 13
11 Slab avalanches exhibit distinct fracture lines 13
12 Slab avalanche nomenclature 14
13 Steep road fillslopes may act as preferred crown locations 14
14 Start zone, track, and runout zone of a confined snow avalanche path at McLean Point 15
15 Unconfined avalanche path on an open slope in the alpine zone ... 15
16 Slab avalanche dependence on start zone slope declination 15
17 New snow avalanche paths cut through mature forest below a steep clearcut near Nagle Creek 16
18 Snow avalanche runout destroying 20 ha of old-growth forest 16
19 Wildfire on steep slopes has created mid-slope openings capable of generating large snow avalanches 16
20 Snow creep and glide deformation 17
21 Snow glide avalanche on a smooth grassy surface at Galena Pass ... 18
22 Forty years of ranked snow water equivalent values from Glacier National Park 20
23 Expected snow water equivalents for various return periods 20
24 Relationship of mean annual maximum snow accumulation with elevation for three sub-regions of the Columbia Mountains 21
25 Snow avalanche areas affecting British Columbia highways 22
26 Recent snow avalanche damage in mature forest 22
27 Vegetative trim lines and subtle colour differences indicate relative frequency of snow avalanche activity 22
28 An indication of snow avalanche frequency from tree ring pattern 23
29 Snow avalanches down the centre path at Fish Lake 23
30 Development in the runout zone has eliminated clues that might otherwise be used to assess snow avalanche frequency 23

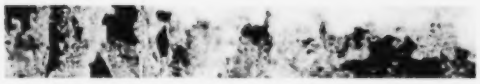
31 Probability of not experiencing one avalanche of a 5-, 10-, or 30-year return period as a function of time 25
32 Vegetative indicator: J-shaped tree trunk indicates probable snow avalanche impact 26
33 Rubble lodged in tree trunk indicates moderate impact pressure ... 26
34 Flagged tree 27
35 Tree trunk snapped by a snow avalanche at Greenslides 27
36 Impact scars from entrained material 27
37 Rubble perched on logging slash deposited by snow avalanche 27
38 Trim lines and debris in valley bottom, Serpentine Creek 27
39 Rubble perched in alder 27
40 Large area of mature timber destroyed by natural avalanching 28
41 Snow avalanches carrying detritus downslope continue to build a fan in the runout zone 28
42 Steep conical fan built by successive snow avalanches carrying colluvium down from an alpine start zone 28
43 An avalanche tarn is an impact feature formed in the runout zone of a large snow avalanche path 28
44 Speed in a large dry avalanche shows rapid acceleration 29
45 Speed and density profiles for a large flowing avalanche 29
46 Large, mixed-motion avalanche with an airborne component 29
47 Large blocks of debris remained intact in a hard slab avalanche 29
48 Snow plastered on this tree trunk indicates flow height of core of avalanche 30
49 Maximum avalanche speed versus square root of slope distance 30
50 Sequence of a powder avalanche 31
51 Large wet avalanche flowing from a confined gully out onto a fan 32
52 Wind exposure class 5 32
53 Avalanche run-up is likely to occur opposite avalanche paths that descend into narrow valleys 34
54 Trees lying upslope on the opposite side of the valley from the avalanche path indicate the destructive forces 34
55 An avalanche that started in a hard dry slab, but melt caused the mass to flow in the runout zone in the mode of a wet snow avalanche ... 34
56 A large wet avalanche that released in spring 34
57 Significant forest damage caused by a snow avalanche at Ruby Mountain 36
58 Conceptual stream flow model for a subalpine stream 36
59 Stream undercuts debris and melts snow 37
60 Rapid breach of a snow avalanche dam caused Mobbs Creek, near Trout Lake in the Kootenays, to damage a trout spawning channel 37
61 Barge torn from its moorings by a snow avalanche from Mt. Rainey ... 37
62 Snow avalanche paths often contain a complex mosaic of plant communities 37

63 Avalanche paths dominated by alder, willow, and herbaceous sites often contain valuable spring bear foods 38
64 Willow, groundsel, and a range of herbaceous species often occur in runout zones 43
65 Snow avalanche path dominated by closed-canopy conifer shrub ... 43
66 Village protected by forest reserved from logging in 1937 45
67 Avalanche start zone defence structures 46
68 Snow support structures built in an opening above a subdivision ... 46
69 Dense forest that was probably destroyed by fire when the railway was built in 1885 47
70 Projections from TIPSY growth model 48
71 Small avalanches may run regularly in long narrow gullies 48
72 Conceptual model of avalanche susceptibility in a regenerating opening in steep terrain with regular, high snow supply 49
73 Damage in a regenerating cutblock from a small avalanche 49
74 Avalanche consequences for traffic will be very high because of the water body below 53
75 ALARP framework for risk assessment and reduction 54
76 Steps in the risk management decision-making process 55
77 Process of continuous risk assessment 55
78 Typical ratios of non-injury industrial incidents to injurious accidents and to fatalities 56
79 Managing the avalanche risk at a logging operation at Doctor Creek 57
80 Winter operations in potential avalanche terrain on private land at Enterprise Creek 58
81 Steep terrain in a recently harvested cutblock on private land 58
82 Avalanches initiating in the steep harvested terrain above the Trans-Canada Highway in the Kicking Horse Canyon 58
83 Harvesting was proposed in an even-aged pine forest where red trees indicate insect attack 59
84 Method used by MoF and MoT to identify proposed harvest blocks that may generate snow avalanches 59
85 Stereopair of Nagle Creek avalanche path 63
86 Slope profile of the Nagle Creek avalanche path plotted from 20-m TRIM contours 65
87 Avalanche mapping for Val d'Isère, France 68
88 Risk map produced by simulation of avalanche runout 69
89 Ministry of Transportation avalanche mapping showing distribution of avalanche paths above highway at Ningunsaw Pass..... 70
90 Terrain mapping for an area in the Interior of British Columbia that has both major and minor avalanche paths 73
91 A landslide initiating below an old road created an opening 75
92 Typical page from an avalanche atlas 76
93 Deterministic application of the PCM avalanche dynamics model 77

94 Terrain parameters used in runout calculation 78
95 a) Radar speed measurements of the frontal pulse of a large avalanche 83
b) Impact pressures measured at two heights on a tower located in the path shown in Figure 95a 83
96 Typical engineered structures used in Europe to prevent avalanche initiation or arrest any small events 85
97 The Total Chance Harvest Plan 87
98 The length of fetch for wind-transported snow is greatly reduced in small openings 88
99 Group selection using small cable or helicopter harvesting systems is appropriate in steep terrain in areas of high snow supply 88
100 Tree patches retained in steeper terrain alter the radiation balance over the snowpack, intercept snowfall, and alter local wind flow ... 88
101 Silviculture prescription specifies retention of high stumps 89
102 Polygon-based 1:5000 scale mapping produced during a Terrain Stability Field Assessment 89
103 Block layout strategies to reduce avalanche susceptibility 90
104 Logs retained by high stumps used to inhibit snow creep and glide in a gully 93
105 Avalanche initiated at a convex change in slope 93
106 Cutblock boundary set too close to gullies where avalanches run ... 94
107 Narrow, vertically oriented cutblocks set out for heliskiing in the Bugaboos are designed to minimize avalanche susceptibility 95
108 A poor bridge location directly in line with the runout of a large snow avalanche path 96
109 Bridge span destroyed by a large snow avalanche 96
110 Alternative bridge design for a high-frequency avalanche path containing a stream that has permanent flow 97
111 Rock ford used to cross the track of a large avalanche path 97
112 Forest roads that cross high in an avalanche track will be affected more often 98
113 Use of this switchback section of road in winter prolongs exposure to avalanches 98
114 Avalanche path on the public road to Shames ski area, Terrace 99
115 Oversteepened road fillslopes that dissect large clearcuts in steep terrain are common points for avalanche initiation 99
116 Causal chain considered in avalanche prediction 102
117 Sample page from field notebook of basic avalanche observations 103
118 Snow profile studies conducted at fracture lines are used to identify failure layers 103
119 Shovel shear test is used to locate, but not rate, a weak layer 104
120 The Rutschblock test requires a slope of 25° (47%) or more 104
121 Snowpack observations conducted at safe sites at the elevation of avalanche start zones 104

122 Standard field notebook set out for a full snow profile observation 106
123 Plot of a snow profile produced by PC application 107
124 Screen from a knowledge-based expert system designed to assist with snow profile interpretation 107
125 A simple, temporary weather observation plot 109
126 Mountaintop remote weather station used for avalanche forecasting ... 111
127 Lower-elevation weather station adjacent to a road in avalanche terrain 112
128 Time series plot of weather data used in avalanche prediction 112
129 Spatial and temporal scales of various weather forecasting techniques 113
130 Predictive skill associated with meso-scale forecasting technique ... 114
131 Explosive charges are delivered by helicopter to start zones to trigger avalanches 118
132 Local experience helps in the identification of preferred targets 118
133 An operator sheltering behind bulldozer was crushed when an avalanche overturned the machine 119
134 Loaded logging truck hit by a Size 3 avalanche 119
135 Avalanche debris removal in Galena Pass near Trout Lake 121
136 Typical rescue transceivers 122
137 Searchers probe a Size 5 avalanche for a victim who was not wearing a transceiver 123
138 Large, blocky avalanche deposit 500 m downslope of the spring snowline 125
139 Searching with a detector device 126
140 Avalanche debris removal in Bear Pass near Stewart 126
141 A slope logged to create a ski run has potential to generate avalanches that might run out into high-value buildings below 129
142 Supporting structures in start zone designed to inhibit avalanches 130
143 Ten-year-old trees offer little protection in a 1.25 m deep snowpack 130
144 Two wet snow avalanches originated in adjacent clearcuts 131
145 The first of two snow avalanches originating in a clearcut stopped just before Highway 6 132
146 Mixed deposit of snow, trees, and colluvium 132
147 Airy Creek avalanche originated in a clearcut and ran into a community watershed 133
148 The block in the foreground avalanched but the two adjacent clearcuts, which have similar topography, were not affected 133
149 Fracture occurred at upper convex slope change and below the road 133
150 Timber damage and soil erosion represent substantial resource losses 134
151 Damage to immature trees in the start zone 134

152 LANDSAT image of the area surrounding Mica Dam showing forest damaged by avalanches at Nagle Creek 134
153 A natural avalanche occurred in the cutblock 135
154 New path resulting from slab avalanche triggered by explosives in clearcut above 138



Management of snow avalanche-prone forest terrain 1

1.1 BACKGROUND

When the U.S. Forest Service appointed snow rangers at Little Cottonwood Canyon, Alta, Utah, in the 1950s, the stage was set for management of snow avalanche hazards in forests of North America. The snow rangers' prime role was promoting safety for land use planning and the winter recreational use of public lands. Monty Atwater and Ed LaChapelle (who later became Professor of Atmospheric Sciences at the University of Washington in Seattle) developed the science of snow avalanche forecasting and explored methods for the control of snow avalanches. Prof. LaChapelle's 1980 analysis of conventional avalanche forecasting remains current 20 years later and sets a foundation for innovations still to be realized. In the late 1960s, the U.S. Forest Service moved its research effort to Fort Collins, Colorado, where meteorologist Pete Martinelli, Jr. assembled a team of snow and avalanche researchers. In 1972, Martinelli and Dr. Ron Perla published the first definitive avalanche handbook for forest land management in North America, the blue-covered U.S. Department of Agriculture *Avalanche Handbook*.

Beginning in the 1950s, the National Research Council of Canada (NRC) and Parks Canada became involved in snow avalanche work at Rogers Pass, B.C., when the Trans-Canada Highway was constructed through the Selkirk Mountains. Parks Canada developed the first snow avalanche forecasting and control program in Canada and laid the foundation for the weather, snowpack, and avalanche observations standards in use today.

A Swiss-trained engineer, Peter Schaerer, P. Eng., was involved in the design of snow avalanche defence structures along the Trans-Canada Highway and subsequently developed the NRC's snow avalanche research program at Rogers Pass. Peter Schaerer went on to participate in the B.C.

Ministry of Transportation Snow Avalanche Task Force set up in response to a snow avalanche that killed seven people in a roadside café near Terrace in 1974. Throughout the 1970s and 1980s, Peter Schaerer published more than 90 papers and chapters documenting research into many aspects of the snow avalanche phenomenon. In 1981, he became the founding president of the Canadian Avalanche Association (CAA), an organization that now has more than 300 members.

A graduate of Professor LaChapelle's program at the University of Washington, Dr. David McClung worked on snow avalanche dynamics research at Rogers Pass and avalanche runout studies while Dr. Perla set up a cold laboratory in Canmore, Alberta, to study snow metamorphism. In 1993, McClung and Schaerer published a completely revised edition of the *Avalanche Handbook*. This comprehensive (and now red-covered) handbook is regarded as the most definitive text in the subject area.

Today Dr. McClung, P. Eng/P. Geo., is chair of Snow and Avalanche Research in the Geography Department at the University of British Columbia and is involved in collaborative research with the British Columbia forest industry. He is internationally regarded as one of the world's foremost snow avalanche researchers and many of his papers are cited in this handbook.

Dr. Bruce Jamieson, P. Eng., of the University of Calgary, is a past president of the CAA and current chair of the CAA Technical Committee. He has undertaken extensive field research to develop and refine snow stability tests for field technicians. His investigations focus on the nature of persistent weak layers that often release slab avalanches in the interior of British Columbia.

The majority of the world's snow and avalanche research is conducted in continental and intermountain climates where wet snow and rain-on-snow are uncommon in winter. Dr. Howard Conway of the Geophysics Department at the University of Washington in Seattle has worked in the Cascade Range and Olympic Peninsula to extend the science of wet snow avalanche prediction. His research is applicable to the management of snow avalanche risk in British Columbia's Coast Mountains and Cascade Range.

In recent years, several tertiary educational institutions, including the Geography and Civil Engineering departments at the University of British Columbia and the Civil Engineering and Geophysics departments at the University of Calgary, have developed courses in snow and avalanche

science. These efforts have helped ensure there is a pool of knowledgeable graduates for furthering this work.

In 1998, the Columbia Mountains Institute of Applied Ecology (CMI) ran a workshop in Revelstoke, B.C. on forestry and avalanches. Issues pertaining to forest harvesting and habitat were discussed.

The CAA, headquartered in Revelstoke, has developed an intensive two-tier, short course, with a training syllabus that focuses on day-to-day snow stability assessment and snow avalanche forecasting. The NRC and the British Columbia Institute of Technology originally established the training system in the 1970s. One course of instruction is aimed specifically at the transportation and resource industries. Extensive practical field experience underpins the formal training. The prerequisite entry criteria for the CAA's Level 2 course are 100 logged days (i.e., typically two winters) of relevant experience within an established snow avalanche program.

The CAA contracted to the Canadian National Search and Rescue Secretariat to produce two documents on avalanche risk and hazard mapping. One is a technical guidebook that is a standard reference for registered professionals involved in avalanche risk assessment in the forest sector. A training course is available for professionals who work with this risk standard.

1.2 AVALANCHE RISK MANAGEMENT IN BRITISH COLUMBIA FORESTS

From 1995 to 2002, the role of professionals in the forest sector who undertook planning, mapping, and terrain assessments was governed by the *Forest Practices Code of BC Act* (1995). Major changes to the Forest Practices Code were being proposed at the time of publication.

The Joint Practice Board (JPB) of the Association of B.C. Professional Foresters (ABCPF) and the Association of Professional Engineers and Geoscientists of B.C. (APEGBC) have published a skill-set document defining appropriate course work, training, and background experience for a qualified registered professional undertaking snow avalanche assessments (Joint Practice Board 2002). The APEGBC has issued a Limited Licence in Geoscience allowing a person so licensed to define snow avalanche hazards, avalanche path boundaries, and the probable limits of travel of future snow avalanches, to identify terrain that could produce snow avalanches, and to estimate snow avalanche return periods. These areas are all considered to be in the realm of Professional Geoscience.

The FPC (1995) gives Ministry of Forests (MoF) District Managers discretion in requiring that a Forest Development Plan (FDP) "will adequately manage and conserve the forest resources." It requires that licensees not carry out a forest practice that could result in "inordinate soil disturbance, or other significant damage to the environment." District Managers have considerable discretion in asking for information to be included in an FDP or in a Silviculture Prescription (SP), and in requiring that Terrain Stability Field Assessments (TSFAs) be undertaken for proposed cutblocks. For example, the Columbia Forest District routinely requests that avalanche hazard assessments be undertaken in cutblocks proposed for harvest.

Within a cutblock, the licensee is responsible for any damage caused by avalanches or another hazard (e.g., insects, disease, fire) until the plantation is declared a "free-growing stand" (as defined in the FPC). If forest adjacent to a cutblock that has not reached the free-growing stage is damaged by any hazard (including avalanches, landslides, fire escape, or windthrow), it is common to amend the SP to allow the licensee to salvage the damaged timber, at the discretion of the District Manager and with the agreement of the licensee. In such instances, the licensee is responsible for reforesting the affected area. Salvage harvesting may also be required. After a cutblock is declared free growing, the Crown is responsible for any subsequent damage.

The *Occupational Health and Safety Regulations* (2001) of the B.C. Workers' Compensation Board (B.C. regulation 296/97, parts 21.85, 26.17, and 26.18) relate specifically to snow avalanche control and safety (Appendix 1). Should there be a conflict between the *Workers' Compensation (Occupational Health and Safety) Amendment Act* and a *Forest Practices Code Act* regulation, then the *Occupational Health and Safety Act*, or the regulation made under that Act, takes precedence.

Transport Canada has the mandate to regulate the use of aircraft for carriage and delivery of explosives onto snow slopes.

Avalanche Risk in Context

Snow avalanches are a common natural hazard in most mountain ranges in British Columbia. It is estimated that more than 300 000 large snow avalanches occur in the province each winter, primarily in forested zones (Stitzinger et al. 2000), but only a very minor proportion of those actually damage property or injure people. Many snow avalanches occur naturally

in remote areas where there are few people and little developed property. Snow avalanches typically kill about 12 people in Canada each winter, although this has increased to about 20 fatalities in recent years. Most of these deaths involve backcountry recreationists. Statistics produced by the CAA indicate that for every fatality caused by an avalanche five more persons are caught but not killed.

Extensive forest damage is a common natural occurrence in mountainous regions of British Columbia and the Pacific Northwest (Figure 1). A survey of avalanching in the province's forests indicates that approximately 10 000 clearcuts are significantly affected by avalanching (McClung 2001a). Most of these cutblocks have been affected by natural snow avalanches running in from above (Figure 2); about 10% of cutblocks surveyed have generated avalanches that have damaged downslope forest resources or infrastructure. Across the province, the latter case may represent a very small proportion of all cutblocks. However, this balance may change in the future as more harvesting occurs on steeper, higher-elevation slopes in high-snowfall areas. Damage from avalanches initiating in clearcuts in both the interior and Coast Mountains of British Columbia involves loss of both timber and soil resources (Figure 3).

FIGURE 1 *Significant forest damage caused by a snow avalanche at Ningunsaw Pass in northern British Columbia.*

FIGURE 2 *Snow avalanches that run into cutblocks or onto roads are relatively common in British Columbia, such as these on the Duffey Lake Road near Lillooet.*

At this stage, it is not possible to rank the effects of snow avalanches with debris flows and landslides in British Columbia forests, but snow avalanches may dominate in the interior, while debris flows and landslides may dominate on the coast (P. Jordan, MoF, pers. comm.).

Natural hazards that threaten human life are commonly rated more highly than damage to economic resources or the environment (Smith 1992). Although snow avalanches regularly kill people in the province and cause substantial forest damage, they pose a less serious problem than earthquakes, volcanic eruptions, floods, and severe storms. The first recorded snow avalanche fatalities in the forestry

sector in British Columbia involved three forest workers who were caught on a forest road blocked by avalanches in the Flathead Valley, near Fernie, while travelling home for Christmas in 1971 (Stethem and Schaerer 1979).

Today, greater concern is being raised about the potential for snow avalanches to be triggered by forest workers or winter recreationists in steep cutblocks (i.e., areas that were not prone to avalanching before harvest). This handbook advocates a risk-based approach to the management of such events on snow avalanche-prone forest terrain (see Appendix 2).

FIGURE 3 *Resource loss in standing forest near Nagle Creek caused by a snow avalanche that initiated in a mid-slope clearcut 200 m above the damaged area. Clearcut harvesting on steep slopes at higher elevations in high snowfall areas of British Columbia is becoming more common, so an increased incidence of forest damage can be expected.*

Snow and avalanche phenomena 2

2.1 SEASONAL SNOW

The shape of new snow crystals is largely a function of temperature and humidity in the atmosphere at the time of formation (Figure 4). Snow crystals are modified during their descent through the lower atmosphere and may become rimed. In extreme cases, they form "graupel," where the underlying crystal is no longer recognized.

The form and properties of new snow can change very rapidly at the surface, particularly when temperatures are warm (i.e., close to 0°C). If significant wind accompanies a snowfall, then snow crystals will be broken into fragments and packed to form a dense, hard surface layer. Rimed snow and graupel can form layers in a snowpack that have properties quite different from those found in other forms of new snow.

The physical properties of snow grains in the snowpack depend principally on temperature and the change in temperature across a layer, as well as its hardness, failure toughness, and strength (McClung and Schweizer 1999). A layer of snow at 0°C (i.e., snow at its melting point) has markedly different properties than a layer that has a sub-zero temperature.

a) Stellar snow crystal. *b) Clusters of columns with plates.* *c) Rimmed needles.*

FIGURE 4 *Some forms of new snow.*

Snow metamorphism, the set of microscopic processes controlled largely by temperature, determines the manner in which snow grains and their bonds change in shape and strength through time (Colbeck 1997). An understanding of snow metamorphism is required by anyone intending to undertake day-to-day snow stability evaluations—a prerequisite for identifying periods of high snow avalanche danger.

There is no universally applicable field test to determine the strength of a snowpack, snow layer, or interface between two adjacent layers, although a number of snow stability tests exist. Often several parameters that correlate with strength must be measured *in situ*, but care must be taken when extrapolating the results because of the high spatial variability that characterizes mountain snowpacks. The CAA's 1995 *Observation Guidelines and Recording Standards for Weather, Snowpack, and Avalanches* presents a range of field tests.

A full discussion of the properties of snow as they relate to avalanche initiation is beyond the scope of this handbook. Readers are referred to McClung and Schaerer's 1993 *Avalanche Handbook* for a comprehensive discussion of the subject.

Snow Accumulation

The seasonal snowpack accumulates layer by layer through the early- to mid-winter period, with more snow often falling at higher than at lower elevations. Numerous studies also show that more snow accumulates in openings than in adjacent forest areas (e.g., Golding 1982; Heatherington 1987).

Many maritime storms have highly variable freezing levels and often bring precipitation in the form of rain to lower slopes and as snow above the freezing level (i.e., the elevation of the 0°C isotherm). In maritime snow environments, the mountain snowpack accumulates as a series of stacked wedges (Weir and Owens 1980).

Some storms may have high freezing levels and bring rain up to the highest mountaintops, leaving crusts within the snowpack at high elevations and melting back the snowline at lower elevations (Figure 5).

In eastern British Columbia, the freezing level is generally below the base of the mountains during winter. The mountain snowpack accumulates in successive layers (Figure 6), with increased accumulations occurring at higher elevations. Rain crusts are less common and the snowline rarely recedes up the mountain.

Maritime storms from the Pacific Ocean produce the highest precipitation in the Coast Range, where mid-elevation sites receive about 3000 mm per year (Schaefer 1978). The greatest snow accumulations tend to occur around the winter 0°C isotherm; (i.e., the average elevation of the freezing level) (D. McClung, University of British Columbia, pers. comm.). Precipitation totals and snow accumulation lessen on mountain chains to the east of the Coast Range (Figure 7).

In the interior of British Columbia, the Selkirk Range features a transitional snow environment, intermediate between the

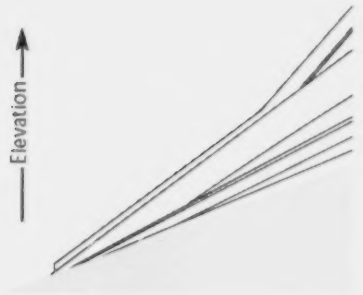


FIGURE 5 *Coast Range snowpacks accumulate as a series of snow wedges truncated by melt at low elevations.*

FIGURE 6 *Typical layering in a winter snowpack. The strength of weaker layers and bonding between layers often controls the stability. A very thin layer of surface hoar buried within the snowpack often forms a critical failure layer.*

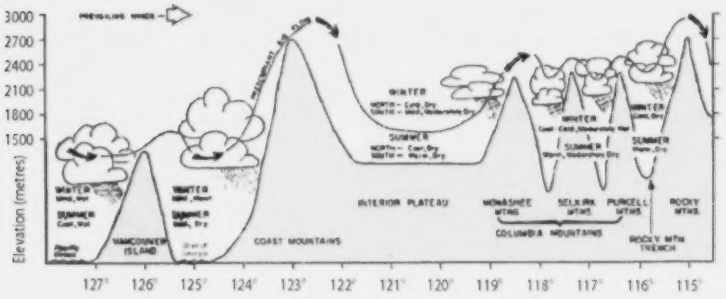


FIGURE 7 *Mountain barriers in southern British Columbia impinging on the prevailing synoptic-scale westerly circulation: Vancouver Island Mountains; Coast Mountains / Northern Cascade Range; Columbia Mountains group (Monashee, Selkirk, and Purcell); and Rocky Mountains (flanking the Prairies). (Source: Chilton 1981).*

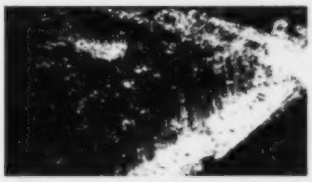
maritime Coast Range snowpack and the continental snowpack found in the Rocky Mountains (McClung and Schaerer 1993, p. 18).

Between snowfalls, the snow surface may be eroded by wind, subject to deposits of rime ice, and affected by sun (particularly on south-facing slopes; north aspects are affected by sun only in spring). Surface hoar crystals commonly grow on the snow surface in the interior of British Columbia. New snow that falls without wind is often cohesionless, but within a few minutes, hours, or days (depending on the environment), bonds may develop between snow grains to form cohesive snow. Cohesion is an important determinant of the type of avalanching that may occur at or below the snow surface.

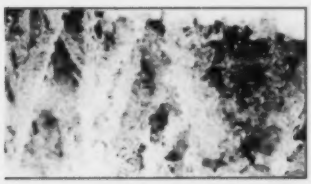
Energy Exchanges over Snow

Winter

During winter, there is often a net loss of energy from the snow surface in open areas (by long-wave radiation). This leads to a cooling of the near-surface layers, particularly on shaded aspects under clear sky conditions. Surface hoar develops when atmospheric water vapour sublimates onto a cold snow surface (Figure 8). A strong temperature gradient in the upper layers of the snowpack (i.e., identified by a notable change in temperature with depth) controls processes that reduce the snow's strength and promote the growth of faceted grains. Energy exchanges are damped under continuous cloud cover or under a forest canopy.



a) Predominantly two-dimensional growth. When the snow surface is cooled by long-wave radiation loss, surface hoar grows as a result of the sublimation of atmospheric water vapour onto the surface.



b) If surface hoar is buried, it may constitute a weak layer in the snowpack that can persist for days or even weeks.

FIGURE 8 *Surface hoar.*

Snow accumulation, snowpack structure, and stability are markedly different under closed-canopy coniferous forest compared to that in openings (Table 1). Wind, temperature, and radiative energy exchanges under deciduous forest (e.g., larch) are intermediate between these two extremes.

Spring

In spring, the snowpack's energy balance changes significantly and there is often a net positive input of solar (short-wave) radiation to the snow's surface. The surface may melt by day, producing liquid water that percolates down through the snowpack. At night, the surface refreezes when energy is lost by long-wave radiation to the atmosphere.

TABLE 1 *Influence of forest cover on the climate parameters that affect snow stability (after Frey and Salm 1990)*

Parameter	In forest openings	Under closed-canopy forest
Wind	Modified by terrain and forest margins. Cornice formation common at ridges. Winds may scour the snow surface.	Wind speed markedly reduced within and below the canopy. Wind shakes the canopy, causing snow to fall, which disturbs the surface of the snowpack below.
Precipitation	Accumulation of snow water equivalent (mm/hr) equal to precipitation rate unless modified by wind.	Canopy interception and sublimation losses reduce accumulation on the ground by typically 30% (snow water equivalent).
Air temperature	Strong air temperature gradients develop immediately above the snow surface.	Lesser air temperature gradients develop immediately above the snow surface.
Radiation	Receipt of short-wave radiation is affected only by topographic shadowing and forest margins. Losses of long-wave radiation promote surface cooling, favouring surface hoar formation and upper-level faceting.	Snow surface is shaded by canopy. Long-wave radiation balance damped and energy losses from snow surface reduced. Surface hoar formation reduced and generally any surface hoar destroyed by snow falling from the canopy.

Melting and refreezing, occurring in the near-surface layers, produce rapid but predictable diurnal changes in snowpack strength. In spring, once they become wet, layer boundaries within the pack become much less distinct and the snowpack increases in density, hardness, and strength. However, free water, produced by surface melt or from rain on fine-grained new snow, can lead to rapid loss of strength and subsequent snow avalanche activity (Conway and Wilbour 1999).

2.2 AVALANCHE PHENOMENA

Snow Avalanche Classification

Avalanches in seasonal snow can be broadly classified by release type (i.e., mode of failure) as either loose snow avalanches or slab avalanches (Table 2). Further classification is based on depth of failure, mode of flow, and moisture of the avalanche mass.

TABLE 2 *Snow avalanche types described according to release mechanism*

Name	Visible characteristic	Description
Loose snow avalanche	Releases at a point	• Movement starts at a point on or near the surface, then spreads out in a triangular form. • Failure involves a local loss of cohesion at the snow surface.
Slab avalanche	Releases along a fracture line	• Snow fails at a weak layer at depth in the pack. • A shear failure propagates under a cohesive slab. • A tensile failure at the crown leaves a characteristic fracture line.

Loose Snow Avalanches

Loose snow avalanches start at a point and leave a characteristic inverted V-shape on the slope (Figure 9). The snow mass set in motion by loose snow avalanches can have sufficient impact to damage poorly located facilities, such as mountain cabins, or to break small trees.

FIGURE 9 *Loose snow avalanches start small but grow in mass as they move downslope. Widespread loose snow avalanching may occur on steep slopes if temperatures rise quickly following a fall of new snow.*

A local loss of cohesion at the snow surface (i.e., commonly new snow or old wet snow) on a steep slope, or an impact from snow falling from trees or rock bluffs, is often all that is required to trigger a loose snow avalanche.

Loose snow avalanches are frequently small, but once in motion they can trigger slab avalanches if unstable snow exists downslope. Loose snow avalanches that involve wet snow can be very destructive if they are confined in a gully.

Slab Avalanches

A snow slab is a layer of cohesive snow that overlies a weaker layer that may fail. A slab avalanche occurs when a fracture propagates under one or more layers of cohesive snow that have accumulated over a weak layer, setting the unsupported slab in motion.

When a slab avalanche releases, it leaves a set of readily identifiable failure surfaces in the surrounding snowpack (Figure 10). A distinct fracture line is evident and can be anywhere from a few metres to a few kilometres long (Figure 11). The failure may involve only the near-surface layers, in older snow lower in the pack; or it may occur at the ground, resulting in a full-depth snow avalanche.

Slab Failure

Immediately before a slab avalanche releases, a shear failure occurs under the slab at the bed surface and at the two flanks. Next, a tensile failure occurs at the crown face and a compressive failure at the stauchwall. The slab is then set in motion.

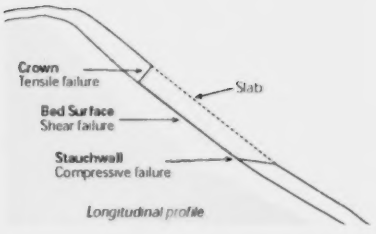


FIGURE 10 *Failure surfaces in a slab avalanche.*

Occasionally, only some of these surfaces fail and the slab remains supported by the remaining surfaces. A characteristic "whumpfing" sound generally indicates occurrence of a shear failure at the slab's bed surface. Johnson et al. (2000) used geophones to record the speed of "whumpf" propagations on surface hoar layers.

Cracks that propagate out in front of snowmobile tracks or from a person on snowshoes can be indicative of imminent slab failure. It may be that the slab is held in place only at the flanks or stauchwall. Partial failures are indicators of high instability and a clear cause for concern.

Slab volume can be calculated according to the dimensions shown in Figure 12.

Very generally, slab dimensions are typically twice as wide as they are long. This relationship enables snow avalanche sizes to be scaled. For example, a small slab measuring 100 m wide and 50 m long (i.e., 0.5 ha) failing to a depth of 1 m will release 5000 m^3 of snow and typically a mass of about 1500 t. A slab avalanche of 10 ha occurring in a clearcut or burn area may set 10 000 t or more of snow in motion. Thus, if a fracture propagates across a cutblock or burnt area, then a large destructive snow avalanche may be generated. In a detailed study of avalanches initiating in clearcuts in British Columbia, McClung (2001a) showed the area damaged downslope to be generally twice the estimated start zone area.

a)

b)

FIGURE 11 *Slab avalanches exhibit distinct fracture lines. Variations in the thickness of the slab are due to cross loading of the slope with wind-transported snow.*

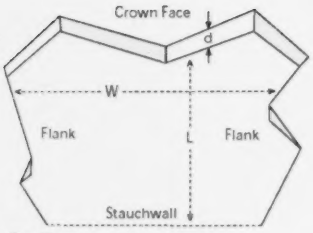


FIGURE 12 *Slab avalanche nomenclature. Estimates of width (W), length (L), and depth (d) enable calculation of slab volume as L x W x d, where:*
L is the length of the slab that fails (i.e., the distance from crown face at the top downslope to the stauchwall)
W is the width of the slab (i.e., average distance from flank to flank)
d is the average depth of the crown face
(After Mears 1992)

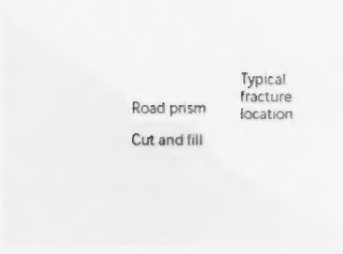


FIGURE 13 *Steep road fillslopes may act as preferred crown locations.*

Avalanches within Clearcuts

A survey of snow avalanche occurrences within clearcuts in the interior and coastal British Columbia regions indicates that there is a clear preference for slab avalanches to release in concave terrain (i.e., bowls) (McClung 2001a).

When a shear fracture propagates under a slab, stress concentrations are likely at convex breaks in slope, below ridges and cornices where the slab thickness tapers, and at anchor points such as rocks or trees. Steep road fill slopes appear to be a common location for avalanche release within clearcuts (Figure 13).

Snow Avalanche Path Nomenclature

Three separate components can be identified in most avalanche paths: the start zone (i.e., analogous to the initiation zone in a debris flow or landslide), the track, and the runout zone (Figure 14).

When a slab avalanche initiates, the released snow slab rapidly accelerates in the start zone to form an avalanche that may gain additional mass downslope. In the track, the avalanche achieves its maximum speed and there may be additional mass gain. In the runout zone, the avalanche rapidly decelerates and deposition occurs. Slope gradient typically decreases down the path from the start zone to the track to the runout zone.

The start zone, track, and runout zone are readily identifiable wherever a snow avalanche becomes confined in a gully, but these components are often less apparent on open slopes (Figure 15).

It is possible for smaller snow avalanches to initiate in the track of a path that spans a large elevational range. Small avalanches may stop within the start zone on a large path.

Studies of a large number of slab avalanches have shown start zones to feature a characteristic range of slope gradients (Figure 16). In a study of slab avalanches initiating in logged areas in British Columbia, McClung (2001a) found a mean start zone angle of 37° (78%) with a standard deviation of 5° ($n = 77$). Harvested start zones ranged in slope from 30 to 50° (58–120%, respectively); refer to Table 3 for conversions from degrees to percent.

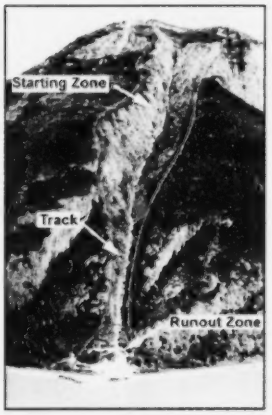


FIGURE 14 *Start zone, track, and runout zone of a confined snow avalanche path at McLean Point, Highway 16 near Terrace. Larger events run out into the Skeena River.*

Start Zone Angles in Clearcuts

New data from cutblock surveys show that many avalanche events initiate on slopes of around 30° (≈ 60%) (McClung 2001a). The survey showed no relationship between snow avalanche size and start zone angle for clearcuts on slopes ranging from 30 to 50°. This finding is significant as it indicates no preferred slope angle for avalanching in blocks proposed for clearcut cable harvesting.

FIGURE 15 *Unconfined avalanche path on an open slope in the alpine zone, running out into forest below.*

Slopes steeper than 55° (140%) are typically too steep to accumulate sufficient snow to produce large slab avalanches. New snow tends to slough off extremely steep slopes as very small avalanches (sluffs) during and immediately after storms.

When a cutblock is harvested on steep terrain in an area with a large snow supply, the area may potentially function as one large start zone (Figure 17). See Appendix 3 for a more detailed discussion of a snow avalanche that occurred in cutblock 83D007-27 at Nagle Creek near the Mica Dam, north of Revelstoke, B.C.

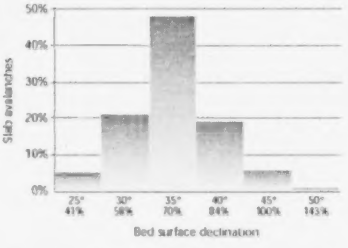


FIGURE 16 *Slab avalanche dependence on start zone slope declination (n = 200). (After Perla 1977)*

FIGURE 17 *New snow avalanche paths cut through mature forest below a steep clearcut near Nagle Creek, destroying 12.5 ha of forest.*

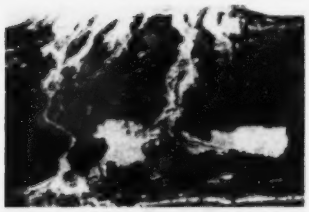


FIGURE 18 *In 1982, a snow avalanche on the right-hand path ran out farther than in the recent past, destroying 20 ha of old-growth forest. The Greenslides avalanche path on Mt. Cartier, east of Revelstoke, is often active in late spring.*

FIGURE 19 *Wildfire on these steep slopes has created steep mid-slope openings capable of generating large snow avalanches. Fire has increased the risk to traffic on the road in the valley bottom.*

Although a large snow avalanche can cut a track through a uniform forested slope, greater damage is likely if the mass of flowing snow is channelled by a local depression or if it enters an incised gully (Figure 18). Once trees are entrained, the avalanche is likely to be more destructive (see the Airy Creek example, Chapter 6.5).

In densely forested mid-slope locations, it is often difficult to define the runout zone because the area may not have experienced avalanching for several hundred years. However, much of the steep terrain in high-snowfall areas of British Columbia was probably prone to snow avalanching prior to forests becoming established in the area after the last glaciation, about 10 000 years before present. It is also likely that many steep, forested slopes in areas of high snow supply have experienced episodes of avalanching following severe wildfires (Figure 19).

TABLE 3 *Conversion of units used in measuring slope angle*

Degrees	Percent	Percent	Degrees
5.0	9	5	3
7.5	13	10	6
10.0	18	15	9
12.5	22	20	11
15.0	27	25	14
17.5	32	30	17
20.0	36	35	19
22.5	41	40	22
25.0	47	45	24
27.5	52	50	27
30.0	60	55	29
32.5	64	60	31
35.0	70	65	33
37.5	77	70	35
40.0	85	75	37
42.5	92	80	39
45.0	100	85	40
47.5	109	90	42
50.0	119	95	44
52.5	130	100	45
55.0	143	105	46
57.5	157	110	48
60.0	173	115	49

Harvesting in the Runout Zone

Harvest planners and operators should consider the risk posed by snow avalanches that might initiate on steeper terrain above a block when planning to harvest on less steep terrain (e.g., on a fan) by ground-based methods.

Creep and Glide

On horizontal ground, snow deformation is termed "settlement"; on sloping ground, deformation produces both settlement and "snow creep." On smooth slopes, snow creep and glide produce very slow movements in the snowpack; rates are in the order of millimetres per day (McClung et al. 1994).

Snow creep involves slow deformation within the snowpack, with faster rates occurring at temperatures close to 0°C. Shear creep occurs when snow grains within a layer on a slope undergo shear deformation due to gravity (McClung and Schaerer 1993, pp. 63–67) as opposed to settlement, which occurs perpendicular to the slope (Figure 20).

Snow glide, a very slow translational slip of the entire snowpack across the ground, occurs preferentially over very smooth surfaces (e.g., on smooth grass slopes or planar rock slabs).

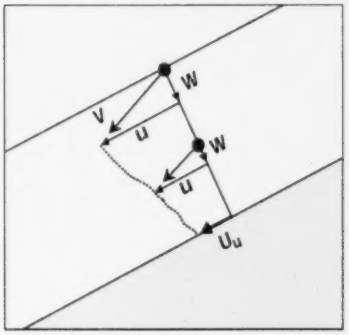


FIGURE 20 *Snow creep and glide deformation*
where:
w is the slope-perpendicular creep velocity (settlement),
u is the slope-parallel velocity,
u_u is the glide velocity,
$(u-u_u)$ is the slope-parallel glide velocity, and
v is the resultant velocity vector.
(Source: SFISAR 1990)

Creep and glide processes tend to be most rapid at the start of winter because the ground is warm and the early snow is of low density (viscosity is proportional to density). Creep and glide may be reactivated in early spring when the snowpack first becomes isothermal at 0°C and liquid water percolates to the base of the snowpack.

Creep and glide can predispose a slope to avalanching (Figure 21). While glide cracks in the snowpack may serve as indicators of likely full-depth avalanching, meteorological parameters (e.g., temperature and net radiation) are better predictors (Clarke and McClung 1999). Glide avalanches are difficult to forecast without on-site instrumentation. Generally, snow glide does not occur in clearcuts because of the rough ground surface.

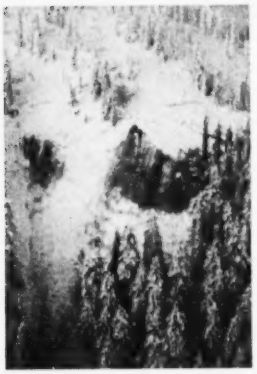


FIGURE 21 *Snow glide avalanche on a smooth grassy surface at Galena Pass. Note the other glide cracks surrounding the glide failure.*

A full-depth avalanche may occur when snow glides over smooth rock or wet ground. Glide avalanches generally occur when meltwater is trapped at the base of snowpack. A glide crack may be evident for minutes to days before failure occurs. Snowmelt and or rain-on-snow events often provide the liquid water that predisposes smooth slopes to full-depth avalanches (Clarke and McClung 1999).

Avalanche Size

In Canada, snow avalanche size is classified according to its destructive potential (Table 4). The classification system embodies the concepts of magnitude, exposure, and vulnerability, which are necessary components of any risk assessment (discussed in Part 2). The avalanche size classification system uses a logarithmic scale of destructive potential. It is therefore similar to the modified Mercalli Scale used for ranking the shaking intensity of earthquakes.

The size of an avalanche is determined by the amount of snow that releases in the start zone, plus the net amount entrained in the track. The size of the start zone (in hectares), the depth of slab failure, and the mechanical properties of the snow govern the initial volume of snow released. Hardness of the slab may control how far a fracture will propagate and thus what proportion of the start zone releases.

If a 10-ha area in a steep cutblock were to fail to a depth of 1 m, and given a typical slab density of 300 kg/m^3, then approximately 30 000 t of snow would be set in motion. By definition, this would generate a Size 4 snow avalanche.

Note that many fatalities occur in small avalanches that typically involve 100–1000 tonnes of snow (Size 2.5 and 3). Jamieson and Geldsetzer (1996) give a broad review of recent snow avalanche accidents in Canada and include detailed summary statistics.

TABLE 4 *Classification of snow avalanche size (source: McClung and Schaerer 1981)*

Size[a]	Destructive potential	Typical		
		Mass (t)	Path length (m)	Impact pressure (kPa)
1	The avalanche is too small to injure a person.	<10	10	1
2	The avalanche could bury, injure, or kill a person.	100	100	10
3	The avalanche could bury and destroy a car, damage a truck, destroy a small building, or break a few trees.	1 000	1 000	100
4	The avalanche could destroy a railway locomotive, large truck, several buildings, or a forest with an area up to 4 ha.	10 000	2 000	500
5	The avalanche could destroy a village or a forest with an area of 40 ha.	100 000	3 000	1 000

[a] Half sizes may be used to describe avalanches that are intermediate between classes.

Notes:

- The classification is designed to describe avalanches in seasonal snow. Events much greater than a Size 5 have occurred when avalanches of glacial ice, permanent and seasonal snow, soil, and meltwater have fallen from steep mountainsides.
- Measurements of slab width, length, and depth, and assumption of an average slab density, allow snow avalanche mass to be calculated. A 1-ha area that releases to a depth of 1 m will typically produce a Size 3 avalanche. This calculation is often the only way of estimating size of a powder avalanche that may blast across an area, destroying vegetation but leaving little mass behind.
- Little is known about penetration of avalanches into mature forest, but typical impact pressures associated with a Size 3 event (100 kPa) are sufficient to break mature trees.
- Different sizing systems are employed elsewhere in the world (including the United States), so care must be taken when reading literature or discussing snow avalanche magnitude with practitioners from other countries. Refer to Appendix D of McClung and Schaerer (1993) for a discussion of other avalanche size classification systems.

Snow Supply

Snow supply is the primary determinant of avalanche frequency (Smith and McClung 1997; McClung 2000). Snow supply can often be estimated by reference to snow survey records (Claus et al. 1984). Historical snow

accumulation data for British Columbia are available on the Internet (Appendix 4). In high snowfall areas along transportation routes, snowfall records often enable reliable estimates of snow supply to be made (the B.C. Ministry of Transportation's Snow Avalanche Program possesses large winter climate data sets).

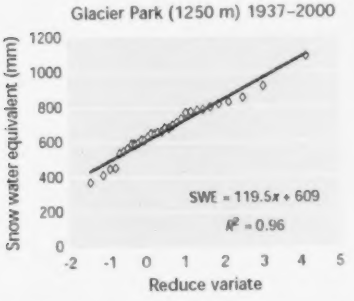


FIGURE 22 *Plot of 40 years of ranked snow water equivalent (SWE) values from Glacier National Park, interior British Columbia fitted to the Gumbel distribution. From this example, the location (u) and scale (b) parameters from the fitted regression equation, SWE= u + b[-ln[-ln(Hazen plotting position)]], are used to predict the snow supply in an avalanche start zone of similar elevation for various return periods (Figure 23).*

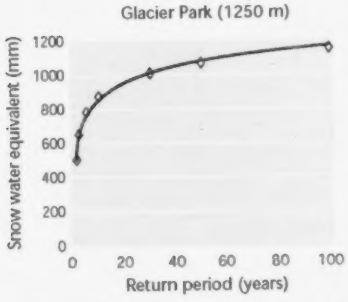


FIGURE 23 *Expected snow water equivalents for various return periods predicted by Gumbel analysis of data in Figure 22 (logarithmic trend line fitted). The return period for the critical snow supply associated with destructive snow avalanches can be determined from this analysis (a threshold of 700 mm is used for the Interior of British Columbia and 1000 mm for the Coast).*

Risk analysis for forestry applications requires that snow accumulation data be analyzed to establish the magnitude of snow supply in avalanche start zones (i.e., annual, 10-, 30-, and 100-year return period snow water equivalents) for any given elevation. McClung (2001a) has undertaken a regional analysis of snow accumulation versus elevation for British Columbia and showed that this relationship can be described by the extreme value statistical distribution developed by Gumbel (1958). Analyses typically use the Hazen plotting position method (Watt et al. 1989, p. 55; Stedinger et al. 1993) (Figures 22 and 23).

Avalanche-prone areas broadly include the steep mid to higher elevations of the coastal British Columbia and Vancouver Island mountains where the mean annual maximum snow accumulation exceeds a threshold of 1000 mm water equivalent, and the mountain ranges in the interior where mean annual maximum snow accumulation exceeds 700 mm water equivalent. High-risk areas are characterized by an annual snow accumulation that exceeds 1000 mm (interior) and 1900 mm (coast) (Stitzinger 2001; McClung

accumulation data for British Columbia are available on the Internet (Appendix 4). In high snowfall areas along transportation routes, snowfall records often enable reliable estimates of snow supply to be made (the B.C. Ministry of Transportation's Snow Avalanche Program possesses large winter climate data sets).

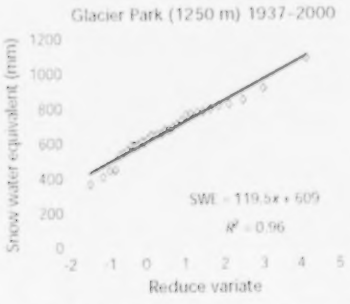


FIGURE 22 *Plot of 40 years of ranked snow water equivalent (SWE) values from Glacier National Park, interior British Columbia fitted to the Gumbel distribution. From this example, the location (u) and scale (b) parameters from the fitted regression equation, SWE = u + b[-ln[-ln(Hazen plotting position)]], are used to predict the snow supply in an avalanche start zone of similar elevation for various return periods (Figure 23).*

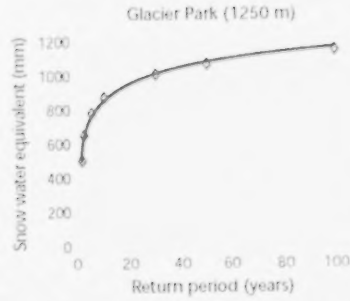


FIGURE 23 *Expected snow water equivalents for various return periods predicted by Gumbel analysis of data in Figure 22 (logarithmic trend line fitted). The return period for the critical snow supply associated with destructive snow avalanches can be determined from this analysis (a threshold of 700 mm is used for the interior of British Columbia and 1000 mm for the Coast).*

Risk analysis for forestry applications requires that snow accumulation data be analyzed to establish the magnitude of snow supply in avalanche start zones (i.e., annual, 10-, 30-, and 100-year return period snow water equivalents) for any given elevation. McClung (2001a) has undertaken a regional analysis of snow accumulation versus elevation for British Columbia and showed that this relationship can be described by the extreme value statistical distribution developed by Gumbel (1958). Analyses typically use the Hazen plotting position method (Watt et al. 1989, p. 55; Stedinger et al. 1993) (Figures 22 and 23).

Avalanche-prone areas broadly include the steep mid to higher elevations of the coastal British Columbia and Vancouver Island mountains where the mean annual maximum snow accumulation exceeds a threshold of 1000 mm water equivalent, and the mountain ranges in the interior where mean annual maximum snow accumulation exceeds 700 mm water equivalent. High-risk areas are characterized by an annual snow accumulation that exceeds 1000 mm (interior) and 1900 mm (coast) (Stitzinger 2001; McClung

and Stitzinger 2002). Major snow avalanches occur only when critical combinations of weather and snowpack conditions exist. The winter of 1998/99 featured about a 50-year return period snowpack and produced large avalanches in clearcuts (D. McClung, University of British Columbia, pers. comm.).

Because snow accumulation is strongly dependent on elevation, it is important to consider the elevation where proposed forest harvesting may be undertaken. Regional analyses of the mean maximum snow accumulation are required to determine the snow supply in avalanche-prone terrain. McClung (2001a) presents curves for sub-regions of the Columbia Mountains (Figure 24). It is appropriate to calculate the return period of winters when a threshold snow supply will be exceeded at the elevation of the cutblock under consideration.

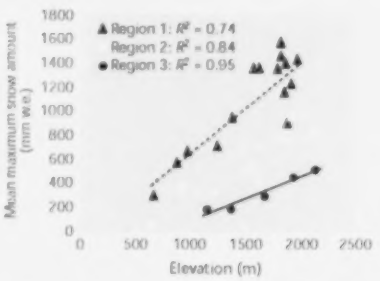


FIGURE 24 *Relationship of mean annual maximum snow accumulation (SWE) with elevation for three sub-regions of the Columbia Mountains, interior British Columbia. Each point is produced by Gumbel analysis of long-term data from a single snowcourse. (McClung 2001a)*

Avalanche Frequency

Analysis of historical snow avalanche records often enables reliable estimates of avalanche frequency to be made. The B.C. Ministry of Transportation and Parks Canada's Rogers Pass snow avalanche programs possess large data sets of snow avalanche occurrence. However, such data must be interpreted with care because explosive-based control programs are suggested to cause about a three-fold increase in snow avalanche frequency (Martinelli 1974).

The proximity of a designated snow avalanche area on a highway in British Columbia is an indicator that the combination of moderate to high snow supply and avalanche terrain exists in the area (Figure 25 shows designated avalanche areas). An open-ended snow avalanche hazard index is used to rate the avalanche hazard on British Columbia highways, based on the frequency and magnitude of avalanching as well as on traffic volumes in the area (Schaerer 1989). The formula that underpins the ratings prevents the hazard index from being applied in adjacent forested areas.

Away from public highways , the frequency of large magnitude (> Size 3) avalanches is difficult to judge because of a lack of data. Estimates can often only be given to an order of magnitude. In low-snowfall areas in

FIGURE 25 *Snow avalanche areas affecting British Columbia highways.*

NOTE: Areas are classified as High avalanche hazard (red), Moderate hazard (yellow), Low hazard (blue), and Very Low hazard (white) based on traffic volumes, exposure, proximity of adjacent paths, and frequency and magnitude of avalanches. Although much of the Coast Mountain Range, from Squamish through Bella Coola to Telegraph Creek, is avalanche-prone, there are few public roads in these areas. (BC MoT Snow Avalanche Programs)

FIGURE 26 *Recent snow avalanche damage in mature forest. Dating the trees will give a first order estimate of snow avalanche frequency.*

FIGURE 27 *Vegetative trim lines and subtle colour differences indicate relative frequency of snow avalanche activity. Note that the avalanche path in the centre of the photo, from Wood Arm, Kinbasket Reservoir, has the potential to destroy additional areas of forest.*

the province—typically low total precipitation areas in the lee of the interior mountain ranges and the coastal mountain ranges that are commonly subject to intense rain rather than snowfall—available records may not capture storms that produced large snow avalanche events.

Vegetative and geomorphic clues must be used to determine areas that were affected by large snow avalanches in the past, and to estimate the potential for major snow avalanches in the future (e.g., Figures 26–30). Dead mature trees, evident amongst young regrowth, do not necessarily indicate a high-frequency avalanche path. Instead, trees may indicate that a large-magnitude, low-frequency event occurred in the recent past. The absence of vegetative clues (e.g., where fans have been cleared for

farming or developed for habitation) increases the uncertainty associated with estimates of snow avalanche frequency or runout potential.

Several approaches should be used when attempting to establish the frequency and magnitude of snow avalanching in forested areas. Generally, few, if any, observational data are available in remote forest areas, but road maintenance personnel (especially grader operators) may have valuable personal knowledge as to the frequency of snow avalanches running out onto roads in an area. Reports of snow avalanches affecting bridges or blocking mainline roads are very useful.

FIGURE 28 *An indication of snow avalanche frequency can be obtained from tree ring pattern, which may show effects of avalanche impact. It may be possible to date some of the scars.*

In British Columbia, the Earth Science Task Force of the Resources Inventory Committee (RIC) has developed a method for assessing landslide hazard, consequence, and risk (Gerath et al. 1996; Table 5). According to the RIC criteria in Table 5, snow avalanche frequency would generally be rated as "high" or "very high." In snow avalanche work, it is generally not possible to discriminate between RIC's "moderate" and "low" relative frequency classes.

Snow avalanche frequency is determined both by climate and terrain. The Coast Range has a higher snow supply, which may increase the frequency of avalanching. In the interior of British Columbia, higher

TABLE 5 *Terminology used to describe frequency of mountain slope hazards (after Gerath et al. 1996; Hungr 1997)*

Relative term	Range of annual: Return period *T* (years)	Probability of occurrence (*Pa*)
Annual	1/1	$Pa \approx 1.0$
Very high	1/20 to 1/2	$0.05 < Pa < 0.5$
High	1/100 to 1/20	$0.01 < Pa < 0.05$
Moderate	1/500 to 1/100	$0.002 < Pa < 0.01$
Low	< 1/500	$Pa < 0.002$

FIGURE 29
Snow avalanches regularly run down the centre path at Fish Lake, between Kaslo and New Denver. Less frequent events may affect other parts of the face. Most of these slopes were affected by fire and may continue to be susceptible to avalanching. Note that snow avalanches also run down the slope below the photographer.

FIGURE 30
Development in the runout zone has eliminated clues that might otherwise be used to assess snow avalanche frequency in these avalanche paths at Three Valley Gap west of Revelstoke.

elevations are more prone to avalanche initiation than lower elevations. Snowpacks in the Interior are dominated by surface hoar and faceted weak layers, which also make this region susceptible to avalanching (McClung 2001a). In the long term, the two effects probably offset one another, but one regime may dominate in any given winter. There is a greater chance of a high-intensity rain-on-snow event occurring in the high-snowfall areas of the Coast Range, leading to wet snow avalanching during the winter.

Avalanche Probability

If snow avalanches are assumed to be rare independent events, then their frequency (or arrival rate at some point of interest such as a forest road or bridge location) can be described using a statistical distribution known as the Poisson process (McClung 2000). LaChapelle (1966) and Smith and McClung (1997) used the Poisson process to calculate an encounter probability for snow avalanches (i.e., the chance that at least one avalanche will reach or exceed a certain point in its path in a given period).

Encounter probability describes the chance that at least one snow avalanche of a specified return period of T years will occur within any given interval of N years, as follows:

$$E = 1 - (1 - \frac{1}{T})^N$$

where:
N is the number of years considered
T is the avalanche return period (in years)

$$T = \frac{1}{Pa}$$

Pa is the annual probability of snow avalanche occurrence (ranging between 0.0 and 1.0)

Mears (1992) used this method to illustrate encounter probabilities for various return periods and lengths of observation record (or period of occupation of a path). Table 6 confirms that there is a good chance of witnessing a 30-year return period event in a human lifetime, but only a slim chance of witnessing a 100-year event. Encounter probability can be used to demonstrate that the length of record should be at least twice as long as the return period to have at least 90% confidence in experiencing the event in question.

The method can also be used to calculate the probability of not experiencing at least one snow avalanche in a given period of observation or exposure. For instance, given that a 100-year return period snow avalanche has an encounter probability of 0.39 in any 50-year period, then the probability of non-encounter is (1–0.39) or 0.61. The probability of not experiencing at least one avalanche decreases with time for any given return period (Figure 31).

TABLE 6 *Encounter probability for various return period avalanches in given periods (after Mears 1992)*

Return period *T* (years)	Length of record (or occupation) *N* (years)	Probability of encounter
10	10	0.65
10	30	0.96
10	50	0.99
30	10	0.29
30	30	0.64
30	50	0.82
30	100	0.97
100	30	0.26
100	50	0.39
100	100	0.63
100	200	0.87
100	300	0.95

Most continuous records of snow avalanche observations in North America are too short (10–40 years) to confidently contain an observation of long return period snow avalanches. Mears (1992) considers that this has led to a poor perception of the snow avalanche hazard in many quarters, as well as the use of poor information in land use planning.

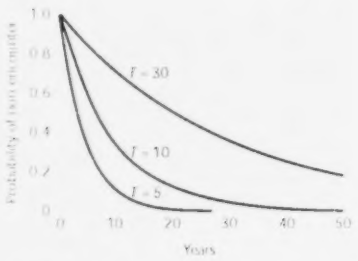


FIGURE 31 *Probability of not experiencing one avalanche of a 5-, 10-, or 30-year return period (T) as a function of time.*

Given the general lack of data in British Columbia and elsewhere in North America, snow avalanche frequency can often only be estimated to an order of magnitude. Mears (1992) recommends that a distinction should just be drawn between 10-year and 100-year return period avalanches, where the return period describes a range of time. With this uncertainty, a "10-year avalanche" may have an actual return period of 3–30 years, while a "100-year avalanche" may have an actual return period of 30–300 years.

Order of magnitude estimates of snow avalanche return period:

10-year avalanche return period $\Rightarrow$ $3 < T < 30$ *years*
100-year avalanche return period $\Rightarrow$ $30 < T < 300$ *years*
(Mears 1992)

The method can also be used to calculate the probability of not experiencing at least one snow avalanche in a given period of observation or exposure. For instance, given that a 100-year return period snow avalanche has an encounter probability of 0.39 in any 50-year period, then the probability of non-encounter is (1–0.39) or 0.61. The probability of not experiencing at least one avalanche decreases with time for any given return period (Figure 31).

Most continuous records of snow avalanche observations in North America are too short (10–40 years) to confidently contain an observation of long return period snow avalanches. Mears (1992) considers that this has led to a poor perception of the snow avalanche hazard in many quarters, as well as the use of poor information in land use planning.

TABLE 6 *Encounter probability for various return period avalanches in given periods (after Mears 1992)*

Return period T (years)	Length of record (or occupation) N (years)	Probability of encounter
10	10	0.65
10	30	0.96
10	50	0.99
30	10	0.29
30	30	0.64
30	50	0.82
30	100	0.97
100	30	0.26
100	50	0.39
100	100	0.63
100	200	0.87
100	300	0.95

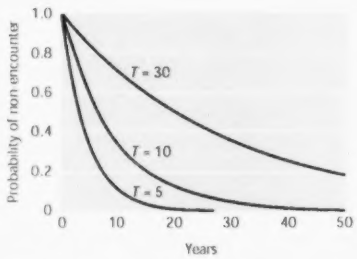


FIGURE 31 *Probability of not experiencing one avalanche of a 5-, 10-, or 30-year return period (T) as a function of time.*

Given the general lack of data in British Columbia and elsewhere in North America, snow avalanche frequency can often only be estimated to an order of magnitude. Mears (1992) recommends that a distinction should just be drawn between 10-year and 100-year return period avalanches, where the return period describes a range of time. With this uncertainty, a "10-year avalanche" may have an actual return period of 3–30 years, while a "100-year avalanche" may have an actual return period of 30–300 years.

Order of magnitude estimates of snow avalanche return period:

10-year avalanche return period $\Rightarrow$ $3 < T < 30$ ***years***
100-year avalanche return period $\Rightarrow$ $30 < T < 300$ ***years***
(Mears 1992)

Vegetative Indicators

Where no snow avalanche occurrence records are available (i.e., most forest situations), vegetative clues may be used to estimate the avalanche frequency (Table 7). Dendrochronological interpretation of increment cores from a few trees (Figure 32), supplemented with diameter at breast height (dbh) data, may assist in establishing the date of the most recent disturbance at any point in the track or runout zone (Burrows and Burrows 1976; Hétu 1990; Jenkins 1994; Boucher et al. 1999).

TABLE 7 *Vegetative indicators of snow avalanche frequency (after Mears 1992; McClung and Schaerer 1993)*

Frequency: at least one event in period	Vegetative indicators
1–10 years	Track supports grasses, shrubs, and flexible species (e.g., alder and willow). Patches of bare soil and shrubs. No trees higher than 1–2 m. No dead wood from large trees except at edges or distal end of runout zone.
10–30 years	Predominantly pioneer species. Dense growth of small trees and young trees of climax species similar to adjacent forest. Broken timber on ground at path boundaries.
30–100 years	Mature pioneering species (non-coniferous) of uniform age and young trees of local climax species. Old and partially decomposed debris.
More than 100 years	Mature, uniform-age trees of climax species. Increment core data useful.

FIGURE 32 *Vegetative indicator: J-shaped tree trunk indicates probable snow avalanche impact. An increment borer can be used to obtain a core, which may show scars and reaction wood.*

FIGURE 33 *Rubble lodged in tree trunk indicates moderate impact pressure.*

Moss and lichen may be polished off the uphill sides of tree trunks and trees may display a J-shaped swept butt. If a snow avalanche entrains talus and rubble, then rocks may be embedded in trees (Figure 33).

In some paths, snow avalanches may run between scattered trees, evidenced by broken lower limbs on all but the downhill side of a tree, a process known as flagging (Figure 34). Note, however, that trees on very windy sites, where rime accumulation is common, may be similarly flagged. Where more destructive snow avalanches occur, tree trunks

FIGURE 34
Flagged tree. A snow avalanche initiating in a clearcut damaged the foliage to the full height of this tree, Akolkolex River.

FIGURE 35
Tree trunk snapped by a snow avalanche at Greenslides near Revelstoke indicates impact pressures of 50–100 kPa.

FIGURE 36
Impact scars from entrained material.

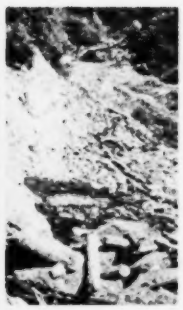


FIGURE 37
Rubble perched on logging slash deposited by a recent snow avalanche.

may be snapped, shattered, or scarred on the upslope side (Figures 35 and 36). In the runout zone, rubble may remain perched on stumps, in live vegetation, or on woody debris after snow avalanche debris has melted (Figures 37–39). This evidence can help distinguish between the effects of windthrow and snow avalanches. Trees destroyed by avalanche blast can be difficult to distinguish from those dropped by windthrow (Figure 40).

FIGURE 38 *Trim lines and debris in valley bottom, Serpentine Creek, North Thompson.*

FIGURE 39 *Rubble perched in alder.*

Geomorphic Indicators

Channelized wet snow avalanches and debris flows are alike in many respects, parts of a continuum of geomorphic processes, separated by a phenomenon known as "slushflow"—the rapid mass movement of water-saturated snow (Hestnes et al. 1994). Slushflows are considered to be relatively common in small creeks in high-rainfall regions of coastal British Columbia and frequently block or wash out culverts and bridges (R. Gee, pers. comm.).

Although the cumulative effects of successive snow avalanches can involve movement of substantial volumes of surficial material, it should be noted that

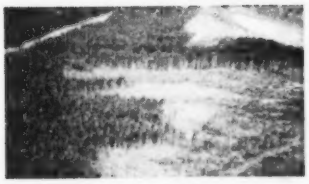


FIGURE 40 *Large area of mature timber destroyed by natural avalanching, at South Rice Brook, tributary to the Kinbasket Reservoir. Note avalanche tarn on right.*

FIGURE 41 *Snow avalanches carrying detritus downslope continue to build a fan in the runout zone, Upper Allan Creek, North Thompson. Note trim lines and destruction of immature trees in the foreground.*

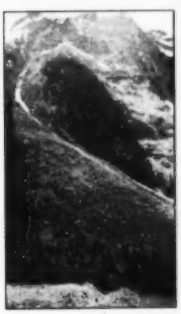


FIGURE 42
Steep conical fan built by successive snow avalanches carrying colluvium down from an alpine start zone, Serpentine Creek, North Thompson.

FIGURE 43
An avalanche tarn is an impact feature formed in the runout zone of a large snow avalanche path. Material deposited in the tarn by avalanches has been subsequently gouged out, building the berm on the downslope edge. The berm has been stabilized by alder and other pioneering vegetation.

many of the gullies in which snow avalanches occur today may owe their geomorphological origin to more active episodes of mass movement immediately following the last glaciation (Butler and Malanson 1990).

In alpine areas, slope angle, slope segmentation, and longitudinal and sedimentological sorting can be used to differentiate rockfall talus from snow avalanche landforms (Jomelli and Francou 2000). Figures 41–43 show a variety of geomorphic indicators, including avalanche tarns and cones.

2.3 AVALANCHE DYNAMICS

At high-consequence or other critical sites, it will be necessary to consider avalanche dynamics. The subject is both technical and complex. The application of runout models or calculation of impact pressures is in the realm of professional engineering and geoscience.

Avalanche Speed and Motion

Avalanches move by sliding or flowing over the surface; some may become airborne. A single avalanche can exhibit all three types of motion.

Dry Snow Avalanches

Avalanche speed varies with the size of the avalanche and the moisture content of both the snow that fails and the snow that is entrained downslope. Dry snow avalanches on steep slopes can accelerate rapidly and quickly attain speeds of 25 m/s or more (90 km/h) in the first 100 m downslope (Figure 44). In recent field measurements at a highly instrumented site in Switzerland, frontal speeds approaching 90 m/s (325 km/h) were recorded in an avalanche with a flow height of 10 m (Dufour et al. 2000).

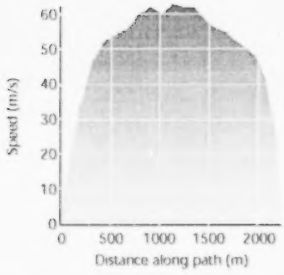


FIGURE 44 *Speed in a large dry avalanche shows rapid acceleration to a maximum of 62 m/s (230 km/h) and very rapid deceleration. (Source: McClung 1990, from measurements by H. Gubler of the Swiss Federal Institute for Snow and Avalanche Research)*

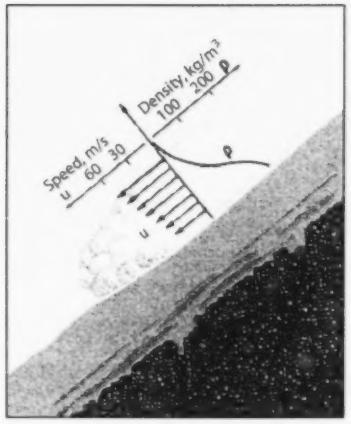


FIGURE 45 *Speed and density profiles for a large flowing avalanche. (After Perla and Martinelli 1976)*

There can be considerable variation in speed and density within a large, mixed-motion avalanche (Figure 45). The flowing component involves a high-density core of granular material (McClung 2001c). At speeds of more than 10 m/s (35 km/h), a low-density dust cloud develops above the flowing component, resulting in a mixed-motion avalanche (Figure 46) (McClung and Schaerer 1993, p 105).

After failure, a snow slab often breaks up into blocks that may disintegrate into dense granular particles. The rate and degree of disintegration depend on the hardness of the slab and geometry of the path (Figure 47).

Immediately after an avalanche, vegetation damage and snow deposited on trees can reveal information about the depth of the flowing and airborne components of mixed-motion avalanches (Figure 48).

Maximum avalanche speed is a function of the scale of the path (Figure 49). McClung (1990) analyzed all known avalanche speed measurements and established two relationships:

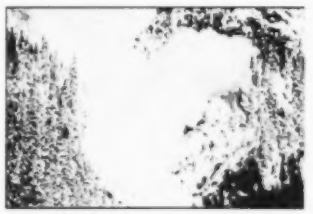


FIGURE 46 *Large, mixed-motion avalanche with an airborne component. The powder cloud may be in excess of 40 m high, while the dense flowing core is probably about 5 m thick.*

FIGURE 47 *Large blocks of debris (> 1 m³) remained intact in a hard slab avalanche that slid 300 m down a steep open slope.*

$U_{max} = 1.5$ (slope distance) $^{0.5}$
and
$U_{max} = 1.8$ (vertical fall) $^{0.5}$, where U = the speed of the snow avalanche.

These relationships should be used to test the validity of any modelled avalanche speeds.

FIGURE 48
Snow plastered on this tree trunk indicates flow height of core of avalanche. Flagged branches higher in the tree indicate height of turbulent, airborne component.

Powder Avalanches

Powder avalanches lack the dense core of a mixed-motion event. The snow is entirely airborne and held in suspension by turbulent eddies. This type of avalanche can be very destructive. Powder avalanches often form when the moving snow mass falls over steep cliffs or bluffs (Figure 50). Small powder avalanches are sometimes called "snow dust" events; while normally harmless, these events can present a serious traffic hazard when visibility is lost.

Powder avalanches can often only be distinguished from high-speed, dry mixed-motion events by the deposit. Fast-moving powder avalanches have sheared off steel bridge guard rails but left no more than a few centimetres of snow in the vicinity (McClung and Schaerer 1993, p. 110). Mears (1992, p. 13) describes extensive damage in a subdivision in Juneau, Alaska caused by a powder avalanche that entrained timber in its path.

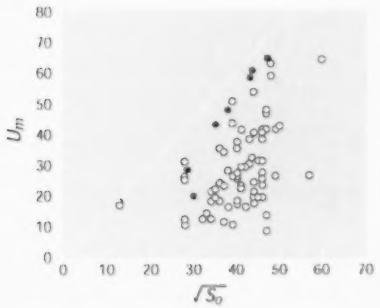


FIGURE 49 *Maximum avalanche speed versus square root of slope distance (S_0) for avalanches from Canada (o), and Switzerland and Norway (*). The envelope $U_{max} = 1.5\ (S_0)^{0.5}$ is shown. (Source: McClung 1990)*

Air Blast

In some terrain, avalanches may build up an air pressure wave that precedes the flowing snow mass and powder cloud. Effects of air blast are difficult to distinguish from damage caused by powder avalanches, unless the event is witnessed.

Air blast is likely to be less destructive than a powder avalanche because the density of the snow dust and air mix

is about 10 times higher than the density of air alone (McClung and Schaerer 1993, p. 107).

Wet Snow Avalanches

Wet snow avalanches generally have no dust cloud and are characterized by their very high surface friction. Large wet snow avalanches can be very destructive. They often entrain vegetation, soil, and boulders in the track and, if they run frequently, can be powerful geomorphic agents (Figure 51).

Wet snow avalanches tend to follow depressions and gullies and can be deflected by changes in terrain and obstacles in the path. Like debris flows, wet snow avalanches sometimes flow in a slow, surging manner. They have been known to make right-angle turns and run down low-friction surfaces such as roads, causing damage in areas that had been considered safe zones. Engineered earthworks in the runout zone can redirect slow-moving wet snow avalanches.

Multiple wet snow avalanches may release in a rain-on-snow event. Individual releases may be small but can coalesce to form large deposits.

Speeds of wet snow avalanches may be considerably less than those of dry events, but the flow densities may be twice as high at 150–200 kg/m^3 (McClung and Schaerer 1993, p. 115).

a) A large slab avalanche descends over steep cliffs and becomes airborne.

b) Larger snow particles fall out and a powder avalanche engulfs the valley below the cliffs.

c) A harmless powder cloud of snow particles in suspension travels more than 2 km down the valley.

FIGURE 50 *Sequence of a powder avalanche.*

2.4 IDENTIFICATION OF SNOW AVALANCHE TERRAIN

Based on field work and air photo interpretation, the U.S. Forest Service established guidelines for identifying and evaluating snow-avalanche terrain (Martinelli 1974). A checklist is presented in Appendix 5.

Any clearcut or forest opening located below a ridge or high plateau in the lee of the prevailing wind is likely to feature increased snow loading. This in turn increases the susceptibility of the area to avalanches after forest harvesting.

Schaerer (1977) proposed a five-level index of wind exposure (Table 8), which can be used to assess the likelihood that the snowpack in a clearcut or burn area may be loaded by drifting snow, and hence prone to avalanching. An example of wind exposure class 5 is shown in Figure 52.

FIGURE 51 *Large wet avalanche flowing from a confined gully out onto a fan, Mt. Bunting, Bear Pass, near Stewart, B.C.*

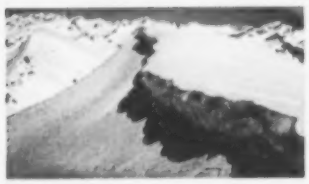


FIGURE 52 *Wind exposure class 5. Cornice development indicates extensive wind-transported snow (right to left).*

TABLE 8 *Ranking of avalanche start zone wind exposure (Schaerer 1972)*

Wind index	Start zone wind exposure
w1	Start zone completely sheltered from wind by surrounding dense forest.
w2	Start zone sheltered by an open forest or facing the direction of the prevailing wind.
w3	Start zone on an open slope with rolls or other irregularities where local drifts can form.
w4	Start zone on the lee side of sharp ridge.
w5	Start zone on the lee side of a broad, rounded ridge or open area where large amounts of snow can be picked up by the wind (Figure 52).

Analysis of 76 destructive avalanche occurrences in harvested blocks in British Columbia by McClung (2001a) showed:

1. a start zone mean slope angle of 37°, a standard deviation of 5°, with a range of 30–50°;
2. a prevalence of moderately concave slopes, with cross-slope concavity being more pronounced than in the downslope direction;
3. ground roughness, vegetation height, and vegetation coverage being potentially important in inhibiting initiation; and
4. a wind exposure index favouring classes w2 and w3 (i.e., moderate but not extreme wind exposure).

Within cutblocks, cross-loading of gullies by wind-transported snow can produce localized snow accumulations that increase avalanche susceptibility. Because wind flow in mountainous regions is a complex subject, it is difficult to predict how wind flows may vary once trees are removed. Foresters considering windfirmness and windthrow potential share this problem (Stathers et al. 1994).

Schaerer (1977) proposed a five-level index of wind exposure (Table 8), which can be used to assess the likelihood that the snowpack in a clearcut or burn area may be loaded by drifting snow, and hence prone to avalanching. An example of wind exposure class 5 is shown in Figure 52.

FIGURE 51 *Large wet avalanche flowing from a confined gully out onto a fan, Mt. Bunting, Bear Pass, near Stewart, B.C.*

FIGURE 52 *Wind exposure class 5. Cornice development indicates extensive wind-transported snow (right to left).*

TABLE 8 *Ranking of avalanche start zone wind exposure (Schaerer 1972)*

Wind index	Start zone wind exposure
w1	Start zone completely sheltered from wind by surrounding dense forest.
w2	Start zone sheltered by an open forest or facing the direction of the prevailing wind.
w3	Start zone on an open slope with rolls or other irregularities where local drifts can form.
w4	Start zone on the lee side of sharp ridge.
w5	Start zone on the lee side of a broad, rounded ridge or open area where large amounts of snow can be picked up by the wind (Figure 52).

Analysis of 76 destructive avalanche occurrences in harvested blocks in British Columbia by McClung (2001a) showed:

1. a start zone mean slope angle of 37°, a standard deviation of 5°, with a range of 30–50°;
2. a prevalence of moderately concave slopes, with cross-slope concavity being more pronounced than in the downslope direction;
3. ground roughness, vegetation height, and vegetation coverage being potentially important in inhibiting initiation; and
4. a wind exposure index favouring classes w2 and w3 (i.e., moderate but not extreme wind exposure).

Within cutblocks, cross-loading of gullies by wind-transported snow can produce localized snow accumulations that increase avalanche susceptibility. Because wind flow in mountainous regions is a complex subject, it is difficult to predict how wind flows may vary once trees are removed. Foresters considering windfirmness and windthrow potential share this problem (Stathers et al. 1994).

Boundary layer wind flow models have been developed for forest areas (Oke 1983, p. 133; Greene et al. 1999), but it is unlikely that they can operate at the scale of a cutblock or predict edge effects or local wind flow perturbations around small, micro-scale terrain features.

Avalanche Susceptibility in Forest Openings

Any clearcut block, burn area, or other forest opening should be regarded as having the potential to generate destructive snow avalanches if it has the following characteristics:

- *a concave profile, either down or across a slope (typically bowls or gullies) with a gradient steeper than 30° (58%);*
- *an adequate supply of new snow;*
- *moderate exposure to wind; and*
- *an average depth of winter snow that is greater than the height of any rough surface features (e.g., projecting stumps or slash).*

2.5 RUNOUT CHARACTERISTICS

Issues related to prediction of avalanche runout distance are central to analysis of consequence associated with forest harvesting on steep terrain.

Avalanche runout distance is correlated with avalanche magnitude. Larger avalanches generally run farther on any given path, with the water content of entrained snow being an important determinant.

Flow conditions along an avalanche path are controlled by the mechanical properties of flowing snow, the nature of the sliding surface and terrain configuration (channelled vs. open slope), and surface roughness of the path. These parameters, along with the mass of snow released, are important determinants of runout distance of extreme snow avalanche events (Mears 1992).

In narrow valleys with high relief, avalanches may not only run out in the valley floor but may also run up slopes on the other side of the valley (Figures 53 and 54).

An avalanche that initiates high on a mountain as a dry slab may entrain wet snow at lower elevations (Figure 55). If a large snow avalanche becomes confined in a gully, then runout distances can be very long, with the mass generally not decelerating until the path gradient decreases to around 8–12° (14–21%) (Mears 1992).

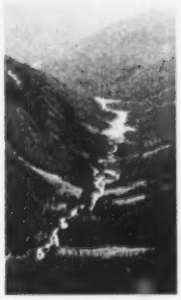


FIGURE 53 *Avalanche run-up is likely to occur opposite avalanche paths that descend into narrow valleys, such as the Cummings River.*

FIGURE 54 *Trees lying upslope on the opposite side of the valley from the avalanche path indicate the destructive forces encountered in a large avalanche.*

FIGURE 55 *This avalanche started in a hard dry slab, but melt, induced during the avalanche's long descent in a broad gully, caused the mass to flow in the runout zone in the mode of a wet snow avalanche. Note the superelevation of the deposit on this outside bend in the path. (Refer McClung 2001c)*

Wet snow avalanches tend to pile up and form deep deposits as they come to rest, often where the avalanche discharges from a confined gully onto a fan (Figure 56). The combination of high density and depth can make wet avalanches very destructive. The slow-moving mass will entrain trees, large boulders, and soil from the path.

2.6 ROLE OF FOREST IN AVALANCHE PROTECTION

Snow accumulation, snowpack layering, the energy balance, and avalanche frequency can be markedly different in closed-canopy forest compared to forest openings (Table 9). These differences can represent important controls on snow stability and susceptibility to avalanching.

Research from Austria indicates that snow avalanches are more likely to occur in harvested areas than in openings created by natural dieback, because much less woody material remains on the slope in harvested areas (Heumader 1999).

Studies from the Canadian Rockies show that young trees with basal diameters exceeding 0.1 m, growing near the top of snow avalanche runout zones, are generally uprooted or broken when

FIGURE 56 *This large wet avalanche released in spring, flowed a long distance, and left a deep deposit. St. Mary Valley, Purcells.*

impacted (Johnson et al. 1985). A theoretical European study indicated that trees with diameters up to 0.3 m may be broken by snow avalanches running as little as 30 m distance downslope (Gubler and Rychetnik 1990).

TABLE 9 *Differences in snow accumulation and stability between forest openings and closed canopy coniferous forest (after Frey and Salm 1990)*

Variable	In forest openings	Under closed-canopy forest
Snow depth	• Controlled by topography	• Less snow accumulates under forest • Greater micro-scale variability (loss due to canopy interception of snowfall)
Snow metamorphism	• Higher rates than under forest • High rates of radiative energy exchange and greater air temperature variation can promote rapid changes in grain form	• Fewer faceted grains because of reduced radiation losses and less air temperature variation
Layering of snowpack	• Continuous layering over large areas • Enhanced formation of weak layers (surface hoar and depth hoar)	• Layer formation disturbed by dripping meltwater and snow falling from canopy
Creep and glide (movements < 1 cm/day)	• Disturbance by snow creep or glide depends on local surface roughness	• Creep and glide insignificant because of rough surfaces
Avalanche type	• Large avalanches possible • Slab releases common	• Small loose snow avalanches common • Large slab avalanche releases are rare but may occur in openings wider than one tree height

2.7 HYDROLOGICAL EFFECTS

Wet snow avalanching often coincides with rain-on-snow events (Figure 57) (Ferguson 2000). Snow avalanches can occur within a few minutes to a few hours of the onset of rain (Conway and Raymond 1993; Carran et al. 2000). When widespread avalanching or a single very large avalanche deposits debris in a mountain stream channel, the nature and timing of stream discharge can be altered (Figure 58).

The hydrological effects of deep accumulations of avalanche snow deposited well below the snowline often counteract each other (de Scally 1992). For example, because the albedo (reflectivity) of snow avalanche

debris is lowered by entrained soil and because lower elevations provide a warmer ambient environment in spring, accelerated melt and consequent increases in peak stream discharge are likely. However, if high loads of surficial materials are entrained in an avalanche, then debris will melt out onto the surface to provide a colluvial veneer that insulates the remaining avalanche snow, retarding further melt. Topographic shadowing of the valley stream channels will also retard the melt of avalanche-deposited snow, compared to the snowmelt rates that would occur on higher, sunny slopes.

FIGURE 57 *Significant forest damage caused by a snow avalanche at Ruby Mountain in the North Cascade Mountains of Washington. The avalanche initiated above timberline and descended into forest during a rain-on-spring-snow event, following a period of sustained warming.*

Snow avalanches rarely dam streams for more than a few hours, although there are noted exceptions (de Scally 1996). Streams often rapidly undercut avalanche deposits (Figure 59).

When large numbers of trees and high volumes of soil are entrained by a snow avalanche, then considerable volumes of woody debris, as well as sediment, will be introduced to the channel system (Figure 60). Geomorphic effects may be similar to those found when lateral bank erosion occurs in streams draining forested watersheds.

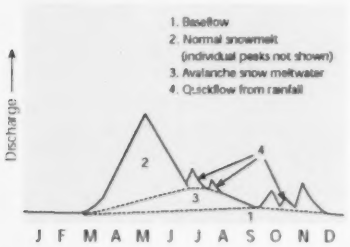


FIGURE 58 *Conceptual stream flow model for a subalpine stream. Hydrograph separated to show (1) base flow, (2) spring snowmelt, (3) avalanche snowmelt, and (4) rain. Avalanche deposits can extend the hydrograph recession, maintaining mid-summer flows. (de Scally 1996)*

The incidence of other rapid mass movement processes (e.g., debris flows) can be increased when snow avalanches run down steep gullies into a stream system, promoting channel disturbance (de Scally 1996).

Snow avalanches can generate significant waves when water bodies are impacted. Given that a large avalanche typically transports 10 000–100 000 tonnes of snow to the runout zone, debris from such events can apply considerable loads to thick ice on frozen lakes. De Scally (1996) cites a report of a snow avalanche that struck a 1.7 m thick ice sheet over a small lake, causing a flood wave that drained 70% of the unfrozen water in the lake.

impacted (Johnson et al. 1985). A theoretical European study indicated that trees with diameters up to 0.3 m may be broken by snow avalanches running as little as 30 m distance downslope (Gubler and Rychetnik 1990).

TABLE 9 *Differences in snow accumulation and stability between forest openings and closed-canopy coniferous forest (after Frey and Holzmann 1990)*

Variable	In forest openings	Under closed-canopy forest
Snow depth	• Controlled by topography	• Less snow accumulates under forest • Greater micro-scale variability (loss due to canopy interception of snowfall)
Snow metamorphism	• Higher rates than under forest • High rates of radiative energy exchange and greater air temperature variation can promote rapid changes in grain form	• Fewer faceted grains because of reduced radiation losses and less air temperature variation
Layering of snowpack	• Continuous layering over large areas • Enhanced formation of weak layers (surface hoar and depth hoar)	• Layer formation disturbed by dripping meltwater and snow falling from canopy
Creep and glide (movements < 1 cm/day)	• Disturbance by snow creep or glide depends on local surface roughness	• Creep and glide insignificant because of rough surfaces
Avalanche type	• Large avalanches possible • Slab releases common	• Small loose snow avalanches common • Large slab avalanche releases are rare but may occur in openings wider than one tree height

2.7 HYDROLOGICAL EFFECTS

Wet snow avalanching often coincides with rain-on-snow events (Figure 57) (Ferguson 2000). Snow avalanches can occur within a few minutes to a few hours of the onset of rain (Conway and Raymond 1993; Carran et al. 2000). When widespread avalanching or a single very large avalanche deposits debris in a mountain stream channel, the nature and timing of stream discharge can be altered (Figure 58).

The hydrological effects of deep accumulations of avalanche snow deposited well below the snowline often counteract each other (de Scally 1992). For example, because the albedo (reflectivity) of snow avalanche

debris is lowered by entrained soil and because lower elevations provide a warmer ambient environment in spring, accelerated melt and consequent increases in peak stream discharge are likely. However, if high loads of surficial materials are entrained in an avalanche, then debris will melt out onto the surface to provide a colluvial veneer that insulates the remaining avalanche snow, retarding further melt. Topographic shadowing of the valley stream channels will also retard the melt of avalanche-deposited snow, compared to the snowmelt rates that would occur on higher, sunny slopes.

FIGURE 57 *Significant forest damage caused by a snow avalanche at Ruby Mountain in the North Cascade Mountains of Washington. The avalanche initiated above timberline and descended into forest during a rain-on-spring-snow event, following a period of sustained warming.*

Snow avalanches rarely dam streams for more than a few hours, although there are noted exceptions (de Scally 1996). Streams often rapidly undercut avalanche deposits (Figure 59).

When large numbers of trees and high volumes of soil are entrained by a snow avalanche, then considerable volumes of woody debris, as well as sediment, will be introduced to the channel system (Figure 60). Geomorphic effects may be similar to those found when lateral bank erosion occurs in streams draining forested watersheds.

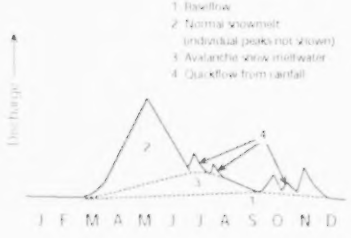

1. Baseflow
2. Normal snowmelt
(individual peaks not shown)
3. Avalanche slow meltwater
4. Quickflow from rainfall
Discharge
J F M A M J J A S O N D

FIGURE 58 *Conceptual stream flow model for a subalpine stream. Hydrograph separated to show (1) base flow, (2) spring snowmelt, (3) avalanche snowmelt, and (4) rain. Avalanche deposits can extend the hydrograph recession, maintaining mid-summer flows. (de Scally 1996)*

The incidence of other rapid mass movement processes (e.g., debris flows) can be increased when snow avalanches run down steep gullies into a stream system, promoting channel disturbance (de Scally 1996).

Snow avalanches can generate significant waves when water bodies are impacted. Given that a large avalanche typically transports 10 000–100 000 tonnes of snow to the runout zone, debris from such events can apply considerable loads to thick ice on frozen lakes. De Scally (1996) cites a report of a snow avalanche that struck a 1.7 m thick ice sheet over a small lake, causing a flood wave that drained 70% of the unfrozen water in the lake.

Snow avalanches from Mt. Rainey above Stewart in northern British Columbia have plunged into the Portland Canal and created surges that have torn barges from their moorings in the vicinity of the log loading area at the port (Figure 61).

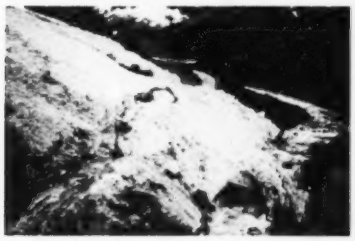


FIGURE 59 *Within a minute of the snow avalanche running into the channel, the stream had undercut the debris and melted a considerable volume of snow.*

FIGURE 60 *Rapid breach of a snow avalanche dam caused Mobbs Creek, near Trout Lake in the Kootenays, to alter course and damage a trout spawning channel.*

2.8 ECOLOGICAL SIGNIFICANCE

Snow avalanche paths are diverse, often productive ecosystems. They provide habitat for a variety of wildlife species. In forested environments, snow avalanche paths form ecotones (or edges) between mature forest and early seral communities. Depending on slope, aspect, elevation, moisture and nutrient characteristics, and frequency of disturbance, seral communities in snow avalanche paths may consist of sparsely vegetated colluvium, herb, shrub-herb, deciduous pole sapling, coniferous pole sapling, or complex mosaics of these community types (Figure 62). As determined by these site factors, early seral communities may proceed normally through successional sequences, persist for long periods of time, or become self-perpetuating disclimax communities no longer capable of reaching edaphic or climatic climax states.

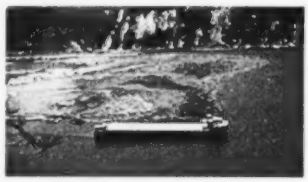


FIGURE 61 *Barge torn from its moorings by a snow avalanche from Mt. Rainey (far side of the harbour), Stewart, B.C.*

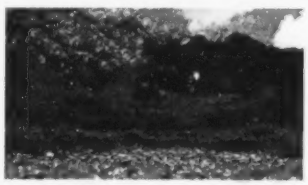


FIGURE 62 *Snow avalanche paths often contain a complex mosaic of plant communities.*

Wildlife habitat values associated with snow avalanche paths have been summarized by Stevens (1995) and Quinn and Phillips (2000). Stevens (1995) identified 35 wildlife species on British

Columbia's provincial "Red and Blue Lists" that utilize snow avalanche path habitats in one or more of the province's 15 biogeoclimatic subzones (Tables 10a and b). Note that while Alpine Tundra (AT) is a non-forested subzone, snow avalanche habitats occur there.

Stevens (1995) defined snow avalanche path plant communities as "shrubland dominated by alders, or other shrubs where periodic snow and rock slides prevent coniferous forest establishment and where moisture is plentiful for much of the growing season; lower areas may support rich herbaceous growth." From a wildlife habitat perspective, snow avalanche paths should be considered at the landscape level. For example, in upper elevations of the Engelmann Spruce–Subalpine Fir (ESSF) biogeoclimatic zone, where there is little fire history, snow avalanche paths provide early seral habitats that are otherwise rare at a landscape level (R. Ferguson, R.P.Bio., pers. comm.). These habitats are used by fox sparrows and warbling vireos, among other bird species, some of which are not found outside of avalanche paths in the ESSF biogeoclimatic zone. Forested margins of avalanche paths are of importance to cavity-nesting birds. Avalanches can shear the crowns from mature conifers on avalanche path margins, rendering these trees susceptible to rot. Avalanche-damaged trees, particularly large-diameter Douglas-fir, are extensively used by primary cavity-nesting birds in the ESSF biogeoclimatic zone.

FIGURE 63 *Avalanche paths dominated by alder, willow, and herbaceous sites often contain valuable spring bear foods such as forbs, horsetail, and fall berries. Ferns, if present, occur only in small numbers. The sites tend to be moist and are often associated with surface water. They occur along drainage channels in the centre of avalanche tracks or in wet runout zones. Aspects vary greatly, so it appears that moisture is the key environmental factor. This site offers very high grizzly bear habitat value based on bear foods (Quinn and Phillips 2000).*

Grizzly Bear Habitat

Grizzly bears are known to use avalanche path habitats extensively, particularly during spring when lush herbaceous communities provide an abundance of forage species including grasses, ferns, horsetails, clover, cow-parsnip, hedyserum, glacier lily, and spring beauty (Mowat and Ramcharita 1999).

The forested edges of avalanche paths provide security (i.e., visual and escape) and thermal cover for grizzly bears close to foraging sites (Mowat and Ramcharita 1999). The runout zone and adjacent valley-bottom streams also offer high-value forage for grizzly bears and a variety of ungulate species (Figures 63–65).

TABLE 10a *Species whose habit includes snow avalanche-prone terrain by British Columbia biogeoclimatic zone (after Stevens 1995)* [1]

Biogeoclimatic zone / subzone		AT	SWB	BWBS	SBPS	SBS	CWH	CDF	BG	PP	IDF	MS	ESSF	ESSFp	ICH	MH
Birds	**Status***															
American kestrel *Falco sparverius*																h,w,l
Golden eagle ***Aquila chrysaetos***		m,e,s	s,b	d,m,k	v,d, k,c	d,k,h, c,x	m,s	c	h,w	x,d	x,d, m,w	x,v, k,m	x,d,m w,c,x	x,d,m	d,k,m,	w,l
Merlin *Falco columbarius*																h,w,l
Northern goshawk ***Accipiter gentilis***		m,e,s	s,b	d,m,k	v,d, k,c	d,k,h, c,x	h,m,s	c	h,w	x,d	x,d, m,w	x,v, k,m	x,d,m	x,d,m	d,k,m, w,c,x	
Northern goshawk ssp. *laingi* *Accipiter gentilis laingi*	Red						h,m,s									h,w
Northern shrike ***Lanius excubitor***			s,b	d,m,k	v,d, k,c	d,k,h, c,x	h,m,s	c	h,w	x,d	x,d, m,w	x,v, k,m	x,d, m,w	x,d, m,x	d,k,m, w,c,x	
Red-tailed hawk *Buteo jamaicensis*									h,w	x,d	x,d, w	x,v, k,m				
White-tailed ptarmigan ***Lagopus leucurus***		m,e,s	b	k										x,d,m		h,w,l
White-tailed ptarmigan ssp. *saxatilis* *Lagopus leucurus saxatilis*	Blue	m														h
Wilson's warbler ***Wilsonia pusilla***					v,d, k,c	d,k,h, c,x	h,m,s	c	h,w	x,d	x,d, m,w	x,v, k,m	x,d,m	x,d,m	d,k,m, w,c,x	h,w,l
Yellow warbler *Dendroica petechia*			s	d,m,k	v,d, k,c	d,k,h, c,x	h,m,s	c	h,w	x,d	x,d, m,w	x,v, k,m		d,k,m, w,c,x	w,l	

1 Refer to Table 10b for biogeoclimatic units.

Table 10a Continued

Biogeoclimatic zone / subzone		AT	SWB	BWBS	SBPS	SBS	CWH	CDF	BG	PP	IDF	MS	ESSF	ESSFp	ICH	MH
Mammals	**Status***															
Bighorn sheep ssp. *californiana* *Ovis canadensis californiana*	Blue	e				d			h,w	x	x,d	x,v,m	x,d	x,d		
Black bear *Ursus americanus*		m,e,s	s,b	d,m,k	v,d, k,c	d,k,h, c,x	h,m,s	c	h,w	x,d	x,d, m,w	x,v, k,m	x,d, m,w	x,d, mw	d,k,m, w,c,x	h,w,l
Black bear ssp. *emmonsi* *Ursus americanus emmonsi*	Blue		s	d			m									
Caribou (northern populations) *Rangifer tarandus*		e,s	s,b	d,m,k	v,c	k,c						v	x,d, m,w	x,d, m,w	c,x	
Caribou (southeastern population) *Rangifer tarandus*	Blue	e		m,k		c,x						k	d,w	d,w	c,x	
Coyote *Canis latrans*		m,e,s	s,b	d,m,k	v,d, k,c	d,k,h, c,x	m,s		h,w	x,d	x,d, m,w	x,v, k,m	x,d, m,w	x,d m,w	d,k,m, w,c,x	w,l
Elk ssp. *nelsoni* *Cervus elaphus nelsoni*		m,e,s	s,b	d,m,k	v	d,h,x	h			x,d	x,d	x,v, k,m	x,d, m,w	x,d, m,w	d,k, m,w	h,l
Elk ssp. *roosevelti* *Cervus elaphus roosevelti*	Blue	m					h,m	c								w
Gray wolf *Canis lupus*		m,e,s	s,b	d,m,k	v,d, k,c	d,k,h, c,x	h,m,s	c	h,w	x,d	x,d, m,w	x,v, k,m	x,d, m,w,	x,d, m,w	d,k,m w,c,x	h,w,l
Grizzly bear *Ursus arctos*	Blue	m,e,s	s,b	d,m,k	v,d, k,c	d,k,h, c,x	h,m,s				x,d,w	x,v, k,m	x,d, m,w	x,d, m,w	d,k,m, w,c,x	h,w,l
Least chipmunk ssp. *oreocetes* *Tamias minimus oreocetes*	Blue												d	d		
Least chipmunk ssp. *selkirki* *Tamias minimus selkirki*	Red												d,w	d,w		

TABLE 10.1 [illegible]

Scientific name and subspecies	AT	SWE	SWBS	SWPS	UKS	CWK	CCF	BG	HP	IDF	MS	CSP	CWP	CP	WH
Taxon[a]															
[illegible]															
[illegible]															
Golden eagle	n,e,v	x,b	d,m,k	v,d	d,k,h	m,v	r	b,w	x,d	x,d	x,v	x,d,m	x,d,m	d,k,m	w,l
Aquila chrysaetos				k,r	r,x					m,w	k,m	w,l,x			
[illegible]															x,w,l
[illegible]															
Northern goshawk	n,e,v	x,b	d,m,k	v,d	d,k,h	h,m,v	r	b,w	x,d	x,d	x,v	x,d,m	x,d,m	d,k,m	
Accipiter gentilis				k,r	r,x					m,w	k,m			w,l,x	
[illegible]															h,w
[illegible]															
Northern shrike		x,b	d,m,k	v,d	d,k,h	h,m,v	r	b,w	x,d	x,d	x,v	x,d,	x,d.	d,k,m,	
Lanius excubitor				k,r	r,x					m,w	k,m	m,w	m,x	w,l,x	
[illegible]								b,w	x,d	x,d	x,v				
[illegible]										v	k,m				
White-tailed ptarmigan	n,e,v	b	k										x,d,m		h,w,l
Lagopus leucurus															
[illegible]															h
[illegible]															
Wilson's warbler				v,d	d,k,h	h,m,v	r	b,w	x,d	x,d	x,v	x,d,m	x,d,m	d,k,m	h,w,l
Wilsonia pusilla				k,r	r,x					m,w	k,m			w,l,x	
[illegible]															
[illegible]															

Table 10 - continued

Biogeoclimatic zone / subzone		AT	SWB	BWBS	SBPS	SBS	CWH	CDF	BG	PP	IDF	MS	ESSF	ESSFp	ICH	MH
Mammals	Status*															
Black bear		m,e,s	s,b	d,m,k	v,d,	d,k,h,	h,m,s	c	h,w	x,d	x,d,	x,v,	x,d,	x,d	d,k,m,	h,w,l
Ursus americanus					k,c	c,x					m,w	k,m	m,w	m,w	w,c,x	
Cougar	Blue						m									
Puma concolor missoulensis																
Caribou (northern population)		e,s	s,b	d,m,k	v,c	k,c						v	x,d,	x,d,	c,x	
Rangifer tarandus													m,w	m,w		
Caribou (southern mountain population)	Blue	e		m,w		c,x						k	d,w	d,w	c,x	
Rangifer tarandus																
Coyote		m,e,s	s,b	d,m,k	v,d,	d,k,h,	m,s		h,w	x,d	x,d,	x,v,	x,d,	x,d	d,k,m,	w,l
Canis latrans					k,c	c,x					m,w	k,m	m,w	m,w	w,c,x	
Elk ssp. *nelsoni*		m,e,s	s,b	d,m,k	v	d,h,x	h			x,d	x,d	x,v,	x,d,	x,d	d,k,	h,l
Cervus elaphus nelsoni												k,m	m,w	m,w	m,w	
Elk ssp. *roosevelti*	Blue	m					h,m	c								w
Cervus elaphus roosevelti																
Gray wolf		m,e,s	s,b	d,m,k	v,d,	d,k,h,	h,m,s	c	h,w	x,d	x,d,	x,v,	x,d,	x,d	d,k,m,	h,w,l
Canis lupus					k,c	c,x					m,w	k,m	m,w	m,w	w,c,x	
Grizzly bear	Blue	m,e,s	s,b	d,m,k	v,d,	d,k,h,	h,m,s				x,d,w	x,v,	x,d,	x,d	d,k,m,	h,w,l
Ursus arctos					k,c	c,x						k,m	m,w	m,w	w,c,x	
Least chipmunk ssp. *cerveris*	Blue												d	d		
Tamias minimus cerveris																
Least chipmunk ssp. *selkirki*	Red												d,w	d,w		
Tamias minimus selkirki																

Table 10a Concluded

B.C. biogeoclimatic zone / subzone		AT	SWB	BWBS	SBPS	SBS	CWH	CDF	BG	PP	IDF	MS	ESSF	ESSFp	ICH	MH
Mammals	**Status***															
Long-tailed weasel ssp. *altifrontalis* *Mustela frenata altifrontalis*	Red	e					m,h				w					w,l
Moose *Alces alces*		m,e,s	s,b	d,m,k	v,d, k,c	d,k,h, c,x	m,s				x,d, m,w	x,v, k,m	x,d, m,w	x,d, m,w	d,k,m, w,c,x	w,l
Mountain beaver ssp. *rainieri* *Aplondontia rufa rainieri*	Blue												m	m		
Mountain goat *Oreamnos americanus*		m,e,s	s,b	d,m,k		c,x	h,m,s			x	x,d,w	x,k,m	x,d, m,w	x,d, m,w	m	w,l
Mule deer ssp. *columbianus* *Odocoileus hemionus columbianus*		m					h,m,s	c							c,x	h,w,l
Mule deer ssp. Hemionus *Odocoileus hemionus hemionus*		m,e	s	d,m	v,d, k,c	d,k,h, c,x	s		h,w	x,d	x,d, m,w	x,v, k,m	x,d, m,w	x,d, m,w	d,k,m, w,c	
Mule deer ssp. *sitkensis* *Odocoileus hemionus sitkensis*			s,b	d			h,m,s						w			w,l
Thinhorn sheep ssp. *dalli* *Ovis dalli dalli*	Red	s	s,b	d												
Thinhorn sheep ssp. *stonei* *Ovis dalli stonei*	Blue	e	s,b	d,m,k		x							m	m,x		
Vancouver Island marmot *Marmota vancouverensis*	Red	m					m									w
Wolverine ssp. *luscus* *Gulo gulo luscus*	Blue	m,e,s	s,b	d,m,k	v,d, k,c	d,k,h, c,x	m,s			x,d	x,d, m,w	x,v, k,m	x,d, m,w	x,d, m,w	d,k,m, w,c,x	w,l
Wolverine ssp. *vancouverensis* *Gulo gulo vancouverensis*	Red	m					h,m	c								w

***Status (notes to Table 10a)**

- The British Columbia provincial *Red List* includes any indigenous species or subspecies (taxa) considered to be extirpated, endangered, or threatened in the province. Extirpated taxa no longer exist in the wild in British Columbia, but do occur elsewhere. Endangered taxa are facing imminent extirpation or extinction. Threatened taxa are likely to become endangered if limiting factors are not reversed. Red-listed taxa include those that have been, or are being, evaluated for these designations.
- The British Columbia provincial *Blue List* includes any indigenous species or subspecies (taxa) considered to be vulnerable in the province. Vulnerable taxa are of special concern because of characteristics that make them particularly sensitive to human activities or natural events. Blue-listed taxa are at risk, but are not extirpated, endangered, or threatened (BC MoELP CDC 1999).

TABLE 10b *Key to biogeoclimatic units referenced in Table 10a*

Biogeoclimatic zone	Subzone
CDF Coastal Douglas-fir	c = coastal Douglas-fir
CWH Coastal Western Hemlock	h = hyper-maritime m = maritime s = sub-maritime
MH Mountain Hemlock	h = hyper-maritime w = windward maritime l = leeward maritime
BG Bunch Grass	h = very dry hot w = very dry warm
PP Ponderosa Pine	x = very dry hot d = dry hot
IDF Interior Douglas-fir	x = very dry d = dry m = moist w = wet
MS Montane Spruce	x = very dry, very cold v = very dry, cool k = dry, cool m = dry, mild
ICH Interior Cedar–Hemlock	d = dry, warm k = dry-moist, cool m = moist, warm w = wet, cool c = moist, cold x = very wet, cold
SBPS Sub-Boreal Pine–Spruce	v = very dry, cold d = dry, cold k = moist, cool c = moist, cold
SBS Sub-Boreal Spruce	d = dry, hot-warm k = dry, cool h = moist, hot-warm c = moist, mild-cool-cold x = wet, cool
BWBS Boreal White and Black Spruce	d = dry, cool m = moist, warm k = wet, cool
SWB Spruce-Willow-Birch	s = scrub b = forested
ESSF Engelmann Spruce–Subalpine Fir	x = very dry d = dry m = moist w = wet
AT Alpine Tundra	m = above MH e = above ESSF s = above SWB

The importance of snow avalanche paths as wildlife habitat has been recognized in provincial and regional guidelines for land-use planning and resource development specifically for the protection of grizzly bear habitat values. For example, the Kootenay–Boundary Land Use Plan (KBLUP) provides for the establishment of Avalanche Path Management Zones (AMZs) to maintain security cover in old and mature forest adjacent to snow avalanche paths that provide grizzly bear habitat values (Government of British Columbia 1995; Kootenay Inter-Agency Management Committee 1996). Modifications to the plan's guidelines have been recommended by Mowat and Ramcharita (1999) and Quinn and Phillips (2000). Given the variable nature of snow avalanche path vegetation communities, the plan provides for a professional biologist (R.P.Bio.) to undertake field assessments to determine the capability of individual snow avalanche paths as grizzly bear habitat. Several projects have been undertaken to map and rank avalanche path habitats for grizzly bears at the local and landscape scales (Mowat and Ramcharita 1999, p. 13).

FIGURE 64 *Willow, groundsel, and a range of herbaceous species often occur in runout zones where the slope becomes gentle and water accumulates. Aspects are generally neutral. Willow dominates other vegetation in this group, but often occurs with subalpine fir or alder. This vegetation type provides high-quality, abundant browse for ungulates throughout the year (Quinn and Phillips 2000).*

Habitat Protection Guidelines

Quinn and Phillips (2000) reviewed the grizzly bear habitat management recommendations from the Kootenay–Boundary Land Use Plan for Tree Farm Licence 14 and recommended a higher level of habitat protection. The authors proposed that:

- An AMZ of 100 m should be established around all high-quality snow avalanche habitat regardless of the distance between paths. Where this habitat is located only on a portion of the entire path (e.g., on a runout zone), then only that portion requires an AMZ.
- Selective harvest retaining 70% of original basal area may be permitted within AMZs. Harvest operations should be scheduled to occur during periods of low forage use by grizzly bears (e.g., spring and early summer operations should be avoided in low-elevation areas).

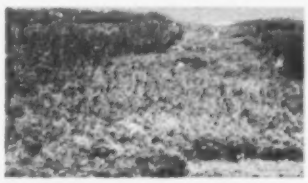


FIGURE 65 *Snow avalanche path dominated by closed-canopy conifer shrub from just below the start zone to the upper runout zone, yielding to an alder-fern-meadowrue-valerian transition, and a cowparsnip-fireweed-grass/sedge meadow. The meadow area is adjacent to a stream and offers valuable, grizzly bear foraging habitat. The adjacent forest is very old ESSF and provides excellent security cover and potential grizzly bedding locations. Most of the path above the runout zone provides little in the way of forage value. The runout portion of this path requires a buffer from forest harvesting (Quinn and Phillips 2000).*

- In snow avalanche path complexes where there is less than 200 m between paths, no forest harvesting should occur between the paths.
- Road construction should avoid runout zones as well as high-quality habitat higher in the track.
- In areas with extensive high-quality snow avalanche habitat, short periods of disturbance followed by long rotations should be planned. Access should be strictly managed following these periods of operation.

Snow avalanche paths with low-quality habitat (e.g., north-facing, dense alder, or continuous low conifer) should not require AMZs.

Avalanche risk assessment 3

3.1 PROTECTION FORESTS

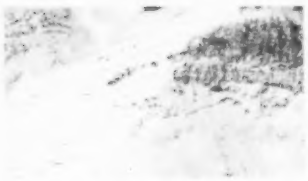
In Europe, where extensive forest clearance occurred in past centuries, mid- and upper-slope forest areas are designated as having a "protection" role wherever downslope facilities are deemed to be at risk (Motta et al. 1999). Many villages are located in potential snow avalanche runout zones in the mountainous areas of Europe (Figure 66). Protection forests are not considered for harvest (Stethem et al. 1996). Holler (1994) reports that it may soon be necessary to extend some avalanche zone boundaries because of the deteriorating health of subalpine protection forests in Austria.

FIGURE 66 *Village protected by forest reserved from logging in 1937 following harvesting of adjoining slopes. An avalanche destroyed trees in the left section of the forest in 1951. Thereafter, additional steel supporting structures were built above the residual forest. Reforestation efforts continue.*

Where historic logging or wildfire has created openings in the protection forests, steel snow-supporting structures are often constructed in the start zones to hold snow in place and to encourage the regeneration of dense forest (Figures 67a and b). The design objective is to produce an overall increase in snowpack stability by adding compressive stresses and reducing shear stresses in weak layers. A second objective is to limit the size of any avalanche mass by retarding the motion or arresting it altogether. The design life of structures must be 50–100 years to allow time for new forests to become well established.

In Switzerland, where inhabited areas exist downslope of historically logged areas, slopes that

range from 30° to 50° are generally considered to warrant avalanche-inhibiting structures. Structures are constructed up to the elevation of the highest expected fracture line. Continuous lines of structures are constructed across the slope 20–50 m apart. The height of a structure is critical for long-term protection, so detailed snow accumulation studies are undertaken as a part of each design. The criteria for design of the vertical height of structures is that they must correspond to at least the 100-year return period snow depth. Typical structure heights used in the Swiss Alps are 3 m, 3.5 m, and 4 m (Margreth 1996). Trees are planted between and below static defence structures.



a) A network of rigid snow-supporting structures installed to resist snow avalanche initiation.

b) Slab avalanche initiation in area not protected with defence structures.

FIGURE 67 Avalanche start zone defence structures.

The Swiss Federal Institute for Snow and Avalanche Research has published standard design specifications in the *Guidelines for Avalanche Protection Utilizing Structures in the Starting Zone* (1990). Installed costs can be of the order of 1 million Swiss francs per hectare (equivalent to about Can. $1 million/ha assuming similar construction costs). Switzerland currently spends 40–50 million Swiss francs annually on afforestation and associated structural measures for avalanche protection (Margreth 2000).

In North America, engineered supporting structures have been employed on very small avalanche paths where property has been placed at risk by logging (Figure 68).

FIGURE 68 Snow support structures built in an opening above a subdivision, Big Sky, Montana. Forest is slowly regrowing between the structures. Such works require professional engineering design in British Columbia.

Where life and buildings are potentially at risk, sensible land use planning in the runout zone will often be a much more cost-effective solution than trying to retain snow on open or harvested slopes. In many cases, it will be cheaper to relocate dwellings or realign a road rather than trying to protect against avalanches of Size 3 or greater. The proposed national standard for avalanche hazard mapping in Canada (McClung et al. 2002) stresses the protective role that forests can play.

Wildfire or logging on steep slopes in areas of high snow supply can create openings that avalanche so frequently that regeneration is exceedingly slow. In the Rogers Pass area, forest burnt over 100 years ago has not regrown beyond a sparse cover because of regular disturbance by snow avalanches (Figure 69).

Avalanches in British Columbia Forests

In the Interior Cedar-Hemlock (ICH) zone of British Columbia, it has been estimated that avalanche initiation may be suppressed if the stand density in potential start zones exceeds 1000 stems per hectare once the mean diameter at breast height (dbh) exceeds 12–15 cm. (However, there are no known surveys that confirm this opinion.)

FIGURE 69 *Dense forest that originally extended to the ridgetop west of Rogers Pass was probably destroyed by fire when the railway was built in 1885. The original railway track was at the bottom of the slope. Construction crews of the era often set the forest on fire to clear the area. Forest not burnt during construction often caught fire later from sparks released by steam engines.*

Projected stand information can be of value when considering the long-term avalanche risk associated with forest harvesting. A block's site index (a measure of optimum tree growth at the 50-year age class) is largely dependent on elevation, aspect, and soil type (Thrower et al. 1991), and can be used to predict rate of regrowth following replanting (Figure 70).

It is suggested that the reduction in avalanche potential in regenerating forests is due primarily to the effect of the canopy projecting above the snow surface, which alters the energy balance and layering of the snowpack. Reduction or elimination of processes that promote surface hoar formation are critical in the Columbia Mountains in particular. Mechanical reinforcement on the snowpack by trees is considered to be a secondary effect.

Successful forest re-establishment will, in the great majority of cases, eliminate the risk of further avalanches. Avalanche initiation is considered to be less likely when tree heights are greater than three times the maximum snow depth. Destructive avalanches start in standing timber only in exceptional circumstances. Conversely, the occurrence of one Size 4 avalanche may lead to permanent site degradation (soil loss) and inhibit forest regeneration.

Interpretation of the output of the forest growth modelling scenario in Figure 72 suggests that the avalanche potential will decrease markedly at

30–50 years after replanting, provided that no avalanches damage restocked areas in the interim.

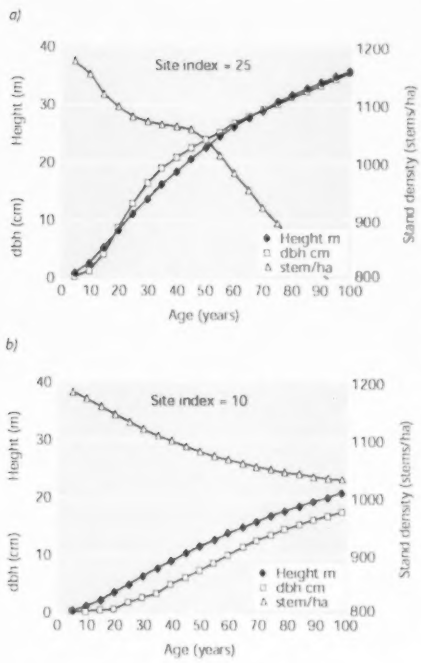


FIGURE 70 *Projections from TIPSY growth model (B.C. Ministry of Forests 1997). Curves are for a) a typical ICH valley floor site and b) a near-timberline site (site indices of 25 and 10, respectively).*

3.2 AVALANCHE RISK CLASSIFICATION

Forestry work in British Columbia typically uses a simple engineering risk model whereby hazard and consequence are independently evaluated. "Hazard" is defined as the likelihood, or probability, of an event (MoF *Forest Road Engineering Guidebook* 2001; landslide risk chapter). Avalanche technicians in the province understand "hazard" to mean the potential to inflict death, injury, or loss to people or to the environment. Unless recognized, this difference in definition of "hazard" may lead to confusion when discussions are conducted between experts from forestry and avalanche disciplines.

Risk Assessment

The proposed Canadian national avalanche risk standard quantifies risk as the combination of avalanche frequency and magnitude (McClung [2002]). In the forest sector, avalanche risk assessments are required to address:

- Long-term (or spatial) problems, where the concern relates to prediction of future avalanche susceptibility (e.g., where an avalanche start zone might be created by forest harvesting or fire, at some time in the future, on previously unaffected terrain).
- Short-term (or temporal) problems, where the

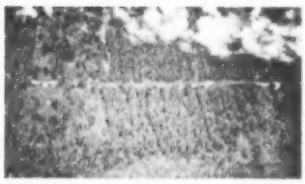


FIGURE 71 *Small avalanches may run regularly in long narrow gullies, but theses events are unlikely to have enough mass to cause significant damage or resource loss.*

30–50 years after replanting, provided that no avalanches damage re-stocked areas in the interim.

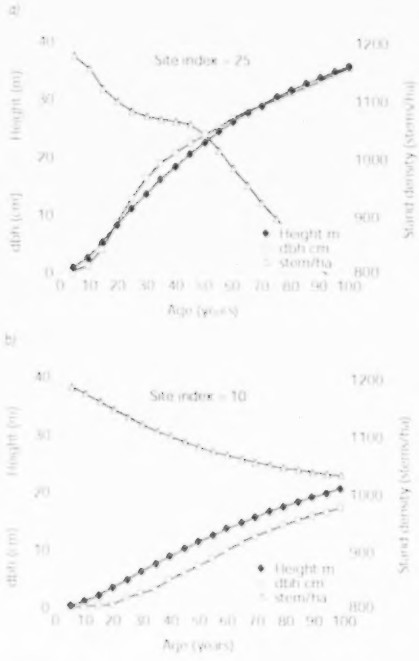


FIGURE 70 *Projections from TIPSY growth model (B.C. Ministry of Forests 1997). Curves are for a) a typical ICH valley floor site and b) a near-timberline site (site indices of 25 and 10, respectively).*

FIGURE 71 *Small avalanches may run regularly in long narrow gullies, but these events are unlikely to have enough mass to cause significant damage or resource loss.*

3.2 AVALANCHE RISK CLASSIFICATION

Forestry work in British Columbia typically uses a simple engineering risk model whereby hazard and consequence are independently evaluated. "Hazard" is defined as the likelihood, or probability, of an event (MoF *Forest Road Engineering Guidebook* 2001; landslide risk chapter). Avalanche technicians in the province understand "hazard" to mean the potential to inflict death, injury, or loss to people or to the environment. Unless recognized, this difference in definition of "hazard" may lead to confusion when discussions are conducted between experts from forestry and avalanche disciplines.

Risk Assessment

The proposed Canadian national avalanche risk standard quantifies risk as the combination of avalanche frequency and magnitude (McClung [2002]). In the forest sector, avalanche risk assessments are required to address:

- Long-term (or spatial) problems, where the concern relates to prediction of future avalanche susceptibility (e.g., where an avalanche start zone might be created by forest harvesting or fire, at some time in the future, on previously unaffected terrain).
- Short-term (or temporal) problems, where the

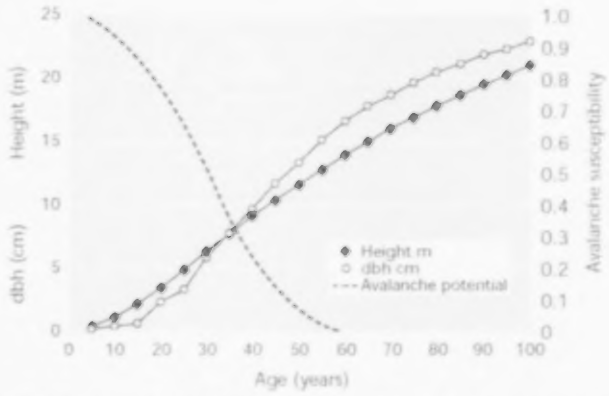


FIGURE 72 *Conceptual model of avalanche susceptibility in a regenerating opening in steep terrain with regular, high snow supply. Note that the precise shape of the "avalanche susceptibility" curve (dotted line) cannot be defined at this time. Tree height and dbh modelled for an ICH stand planted at 1400 stems/ha with site index 13; typical midslope cutblock regrowth. (Projected dbh and height from TIPSY growth model, B.C. Ministry of Forests 1997.)*

concern relates with real-time avalanche assessment and forecasting in recognized avalanche terrain. Public and worker safety, and resource protection, are key issues.

FIGURE 73 *Damage in a regenerating cutblock from a small avalanche that initiated in a clearcut above. Many similar small events go unnoticed each winter.*

In this handbook, the term "likelihood" is defined as an "expert's degree of belief" that an event will occur in a specified time period, given various data and site-specific information (Edwards 1992, p. 9; Vink 1992; Einstein 1997; McClung 2001a). When assessing snow avalanche risk, an expert will draw on background knowledge and experience, principles of engineering and geoscience, and site-specific climate and terrain information to assess the likelihood of an avalanche occurrence within a given spatial and temporal setting (Table 11).

Bayes' theorem may be used in avalanche risk assessment, to enable observational information to be combined with professional opinion, quantified as a subjective probability (Wu et al. 1996; Einstein 1997).

Tables 11–13 present an avalanche risk assessment method that is used to

rate the avalanche risk prior to harvesting. The assessment equation has the form: risk = (frequency) × (magnitude [i.e. expected damage]).

At the landscape level, the key question to address in the Forest Development Plan is whether snow avalanches will initiate if clearcut harvesting is undertaken and, if so, what the consequences will be. During the planning process, it should be possible to locate mainline and secondary roads to minimize the avalanche risk. It is recommended that avalanche frequency be considered over the length of time that it will take for a closed-canopy forest to develop above the height of the 30-year maximum snowpack. That time will depend on the block's site index.

A detailed risk assessment should be undertaken during block layout, ideally as part of the terrain stability field assessment, before specifications for the silviculture prescription are completed. Avalanche runout modelling should be undertaken for any downslope element at risk (e.g., a railway, highway, road, transmission line, fish stream, or water intake on a stream) and an estimate made of the vulnerability of that facility or feature. Measures to mitigate avalanche hazards faced by workers in winter should be addressed during preparation of the silviculture prescription.

TABLE 11 *Estimate of avalanche likelihood from site-specific observations and analysis of climate data*

Likelihood	Frequency range (one event in period)	Annual avalanche frequency	Description
Near certain	< 3 years	1:1	The event will probably occur in most circumstances.
Likely	3–30 years	1:10	The event should occur at some time (highly likely in a human lifetime).
Unlikely	30–300 years	1:100	The event may occur at some time (unlikely in a human lifetime).

The risk analysis matrices presented in Tables 12 and 13 can be used to rank both short- and long-term risk, but different management responses are appropriate, as recommended in Table 4.

Assessing Risk to Forest Cover

To prevent damage to the forest cover, the recommended acceptable risk is a Size 3 avalanche with an average frequency of less than 1:10 years, or a Size 2 avalanche with an average frequency of less than 1:1 years. The risk

matrices below are constructed on the basis of three orders of magnitude, avalanche frequency, and consequences rated qualitatively (proportionally to the risk). Risk of damage to forest cover is rated as low (L), moderate (M), and high (H).

TABLE 12 *Risk ratings for expected avalanche size and expected avalanche frequency for forest harvest resulting in damage to forest cover (source: McClung [2002]). Risk is rated qualitatively as low (L), moderate (M), and high (H)*

Frequency range (events/yr)	Average frequency (events/yr)	Qualitative risk for avalanche size 2	3	> 3
>1–1:3	1:1	M	H	H
1:3–1:30	1:10	L	M[a]	H
1:30–1:300	1:100	L	L	H

[a] The proposed Canadian national avalanche risk standard for forest harvesting (Size 3 with 10-year return period; bolded), is considered to be on the border between moderate and high risk (McClung et al. 2002). However, due to uncertainty in the estimate, other categories have the same moderate risk rating. Moderate risk will normally warrant modification of the harvest design.

Notes:

- For damage to forest cover, the risk is nominal for avalanches of less than Size 2 (see p. 19 for avalanche size definitions).
- Avalanches of Size 4 or larger are unacceptable at any return period following logging. Size 4 avalanches initiating in cutblocks can create permanent new avalanche terrain by degrading soil and vegetative cover, which is unacceptable in an environmental standard. Size 4 avalanches may introduce significant amounts of soil, rocks, and logs to stream channels. The effects may be similar to large debris flows.
- Frequent Size 2 avalanches can damage small seedlings and branches during regeneration. This, with the inherent uncertainty associated with the field estimation, produces moderate risk for annual avalanches (1:1).
- There may be additional site-specific instances where a Size 2 avalanche, at a 1 year in 10 return period, may pose risk to downslope or in-stream values, such as critical fish spawning reaches or locations where a stream blockage or avulsion is likely. In such instances the risk may be revised upwards, based on professional judgement.

Assessing Risk above Transportation Corridors, Facilities, or Essential Resources

When downslope transportation corridors (e.g., highways or railways), facilities (e.g., occupied or unoccupied structures), essential resources (e.g., registered community, domestic, or commercial watersheds or important fisheries), or other concerns may be affected by avalanche initiation from logging, the acceptable risk must be more conservative than if timber resources alone are affected. For this application, the recommended acceptable risk is a Size 3 avalanche with an average frequency

of less than 1:30 years, or a Size 2 avalanche with an average frequency of less than 1:3 years. Table 13 shows the applicable risk matrix analogous to Table 12 for timber resources.

TABLE 13 *Risk ratings for expected avalanche size and frequency for forest harvest when downslope transportation corridors, facilities, or essential resources may be affected (source: McClung [2002]) Risk is rated qualitatively as low (L), moderate (M), and high (H)*

Frequency range (events/yr)	Average frequency (events/yr)	Qualitative risk for avalanche size 2	3	>3
>1–1:10	1:3	M	H	H
1:10–1:100	1:30	L	M[a]	H
<1:100	1:300	L	L	H

[a] The reference level of risk (Size 3 with 30-year return period; bolded) is considered on the border between moderate and high risk. However, due to uncertainty, other categories have the same risk rating. moderate risk will normally require modification of the harvest design.

Notes:

- In the applications described (damage to downslope resources), the risk is minimal for avalanche sizes less than 2.
- In rail applications, forest harvest practices that are likely to produce avalanches contaminated with debris (other than snow) onto the rails are unacceptable in practice.
- In general, avalanches greater than Size 2 are unacceptable on thoroughfares in Canada when open to the travelling public. Moderate risk will imply efficient control and closure procedures.
- Roads with low traffic volumes, such as logging roads, may follow the less conservative matrix given in Table 12.
- Avalanches of Size 4 (or larger) that are likely to result from forest harvest are unacceptable in practice. Such avalanches can create permanent new avalanche terrain above the location of concern, which can mean a high frequency of avalanches reaching the downslope resource. Size 4 avalanches can contain significant amounts of soil cover and other debris (e.g., logs, rocks) and the destructive effects may be considered comparable to large debris flows.

Consequence

The revised *Forest Road Engineering Guidebook* (B.C. Ministry of Forests 2001) contains an in-depth discussion of landslide consequence and presents a matrix-based rating system, which differentiates between on-site, downslope, and downstream elements at risk. In the proposed Canadian national avalanche risk standard employed herein, impact forces and runout distances are modelled to determine consequence (McClung [2002]).

Figure 74 illustrates a potential snow avalanche situation where consequence varies markedly depending on what element at risk is under consideration.

TABLE 14 *Examples of risk management strategies*

Level	Risk	Appropriate risk management strategy: Protection of forest resources Protection of environment	Appropriate risk management strategy: Public and operational safety issues
H	High	Avoid development or forest harvesting. Mitigation or remediation usually too expensive compared to economic returns.	Risk to forest workers, downslope transmission and transportation corridors, or residents is unacceptable. Avoid.
M	Moderate	Qualified registered professional to assess avalanche risk during a terrain stability field assessment by estimation of destructive potential and return interval of avalanches at point of interest. Elements at risk identified and their vulnerability evaluated. Modification of clearcut harvesting prescriptions developed to reduce likelihood of avalanche initiation or lateral or lineal extension of existing avalanche paths. Roads and bridges relocated.	Responsibility for snow stability and avalanche danger should be clearly specified. Senior management committed to development and maintenance of avalanche safety program. Temporary shut down procedures accepted as part of work program. Risk may be avoided by scheduling harvesting for summer. Experienced avalanche technician with CAA Level 2 qualification retained to implement efficient avalanche control and closures.
L	Low	Quantify and accept the risk.	Manage risk by standard occupational health and safety regulations and safe work procedures.

Risk Management Strategies

Risk management strategies often draw a distinction between:

- High Likelihood – Low Consequence events and
- Low Likelihood – High Consequence events

Different risk management responses are often warranted for each of the combinations (Strahlendorf 1998) (Table 15).

FIGURE 74 *Any avalanche originating in this cutblock will be of low consequence with respect to the timber resource but the consequences for traffic hit by an avalanche on the road will be very high because of the water body below.*

TABLE 15 *Appropriate risk responses (source: Elms 1998)*

Likelihood	Consequence	
	High	Low
High	Avoid or reduce risk	Adopt quality safety management systems
Low	Treat very carefully Reduce consequence	Accept risk

The avalanche risk on snow-covered slopes over 60% can seldom, if ever, be reduced to zero (Figure 75). Whenever risk is judged to be excessive, reduction strategies generally adopt the "ALARP" principle: the residual risk should be "As Low As is Reasonably Practicable" (Canadian Standards Association 1997; Keey 2000). Fell and Hartford (1997) distinguish between risk tolerability and acceptability for developments in British Columbia.

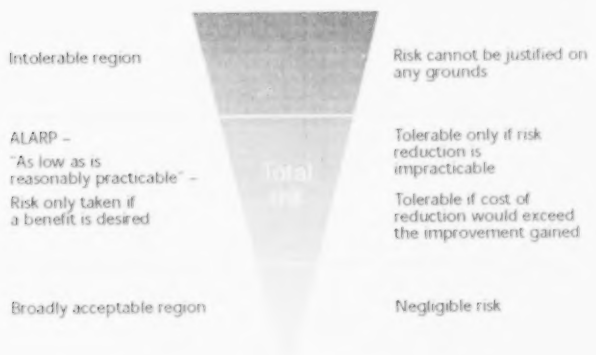

Intolerable region
Risk cannot be justified on any grounds
ALARP –
"As low as is reasonably practicable" –
Risk only taken if a benefit is desired
Tolerable only if risk reduction is impracticable
Tolerable if cost of reduction would exceed the improvement gained
Broadly acceptable region
Negligible risk

FIGURE 75 *ALARP framework for risk assessment and reduction. (After Canadian Standards Association 1997, p. 25; Morgan 1997)*

TABLE 15 *Appropriate risk responses (source: Elms 1998)*

Likelihood	Consequence	
	High	Low
High	Avoid or reduce risk	Adopt quality safety management systems
Low	Treat very carefully Reduce consequence	Accept risk

The avalanche risk on snow-covered slopes over 60% can seldom, if ever, be reduced to zero (Figure 75). Whenever risk is judged to be excessive, reduction strategies generally adopt the "ALARP" principle: the residual risk should be "As Low As is Reasonably Practicable" (Canadian Standards Association 1997; Keey 2000). Fell and Hartford (1997) distinguish between risk tolerability and acceptability for developments in British Columbia.

Intolerable region
Risk cannot be justified on any grounds
ALARP –
"As low as is reasonably practicable"
Risk only taken if a benefit is desired
Tolerable only if risk reduction is impracticable
Tolerable if cost of reduction would exceed the improvement gained
Broadly acceptable region
Negligible risk

FIGURE 75 *ALARP framework for risk assessment and reduction. (After Canadian Standards Association 1997, p. 25; Morgan 1997)*

Risk management typically involves six steps (Figure 76). Risk communication with all stakeholders is an important part of each step.

FIGURE 76 *Steps in the risk management decision-making process. (After Canadian Standards Association 1997, p.7; Keey 1998)*

Risk assessment is regarded as a continuous iterative process (Figure 77). The monitor and review process is important because ongoing forest development may increase the avalanche risk over time. Review gives management verification as to the success of risk reduction strategies in use. Continuous risk assessment not only applies to the day-to-day evaluation of snow stability and avalanche danger, but also to the overall avalanche risk in an operating area over time.

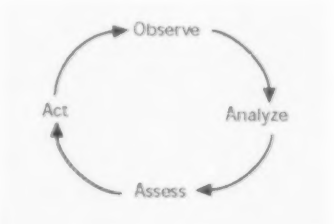


FIGURE 77 *Process of continuous risk assessment. (Elms 1998)*

Forest managers should watch for "insidious" risks that may develop as harvesting moves onto higher, steeper terrain or, locally, where steep blocks are harvested above camps, mills, scales, residential areas, transportation corridors, bridges, or power lines.

Once a detailed risk assessment is complete, an experienced avalanche practitioner should be consulted to develop a suitable winter safety program.

Responsibility for Risk Management

Avalanche risk management is everyone's responsibility. Risk management should be integrated and owned throughout a company or operation. A sound objective is to develop a corporate safety culture above and beyond Workers' Compensation Board requirements. There should be one, clearly identifiable individual who assesses the overall situation each day during the avalanche season. That person shall be

referred to as the "officer responsible for avalanche risk management." In larger organizations, that officer does not do all the work, but provides policy and advice on setting up risk management systems and then monitors what is being done.

An avalanche accident and incident log should be maintained to assess the frequency of avalanche hazards encountered in the forest. A proactive approach to record-keeping will function only if the workers and management view the process in a positive light with an objective of improving occupational health and safety. Contractors should not be penalized for tracking or reporting incidents or for making conservative decisions regarding their own safety.

Accident and Incident Logs

It must be recognized that while an incident and accident log can help a forest company plan its response to the avalanche hazard, it may fail to give adequate warning if the operating environment changes. Logging operations moving into steeper terrain or higher elevations, or operations that encounter an unusual combination of weather and snowpack conditions, may face an abrupt increase in the avalanche risk.

FIGURE 78 *Typical ratios of non-injury industrial incidents to injurious accidents and to fatalities.*

Many studies of industrial accidents indicate that a large number of non-injury incidents are precursors of accidents and fatalities (Figure 78).

3.3 OWNERSHIP OF RISK IN FOREST OPERATIONS

It is recommended that an overview avalanche risk assessment be undertaken for portions of the operating area, as a part of "total chance planning," where harvesting is planned for slopes steeper than 30° (58%), especially in areas of high snow supply. This may be achievable by a combination of air photo interpretation, GIS analysis, and limited field verification. In high snow supply areas, it is appropriate for the qualified registered professional to incorporate a more detailed avalanche assessment at the block level as a part of a terrain stability field assessment.

Risk management typically involves six steps (Figure 76). Risk communication with all stakeholders is an important part of each step.

Risk assessment is regarded as a continuous iterative process (Figure 77). The monitor and review process is important because ongoing forest development may increase the avalanche risk over time. Review gives management verification as to the success of risk reduction strategies in use. Continuous risk assessment not only applies to the day-to-day evaluation of snow stability and avalanche danger, but also to the overall avalanche risk in an operating area over time.

Forest managers should watch for "insidious" risks that may develop as harvesting moves onto higher, steeper terrain or, locally, where steep blocks are harvested above camps, mills, scales, residential areas, transportation corridors, bridges, or power lines.

FIGURE 76 Steps in the risk management decision-making process (after Canadian Standards Association 1997, p. 7; Kay 1998).

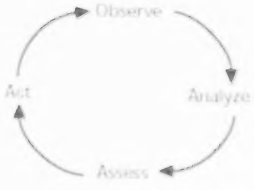


FIGURE 77 Process of continuous risk assessment (Kay 1998).

Once a detailed risk assessment is complete, an experienced avalanche practitioner should be consulted to develop a suitable winter safety program.

Responsibility for Risk Management

Avalanche risk management is everyone's responsibility. Risk management should be integrated and owned throughout a company or operation. A sound objective is to develop a corporate safety culture above and beyond Workers' Compensation Board requirements. There should be one, clearly identifiable individual who assesses the overall situation each day during the avalanche season. That person shall be

referred to as the "officer responsible for avalanche risk management." In larger organizations, that officer does not do all the work, but provides policy and advice on setting up risk management systems and then monitors what is being done.

An avalanche accident and incident log should be maintained to assess the frequency of avalanche hazards encountered in the forest. A proactive approach to record-keeping will function only if the workers and management view the process in a positive light with an objective of improving occupational health and safety. Contractors should not be penalized for tracking or reporting incidents or for making conservative decisions regarding their own safety.

Accident and Incident Logs

It must be recognized that while an incident and accident log can help a forest company plan its response to the avalanche hazard, it may fail to give adequate warning if the operating environment changes. Logging operations moving into steeper terrain or higher elevations, or operations that encounter an unusual combination of weather and snowpack conditions, may face an abrupt increase in the avalanche risk.

Many studies of industrial accidents indicate that a large number of non-injury incidents are precursors of accidents and fatalities (Figure 78).

FIGURE 78 – *Typical ratio of non-injury industrial incidents to injurious accidents and to fatalities.*

3.3 OWNERSHIP OF RISK IN FOREST OPERATIONS

It is recommended that an overview avalanche risk assessment be undertaken for portions of the operating area, as a part of "total chance planning," where harvesting is planned for slopes steeper than 30° (58%), especially in areas of high snow supply. This may be achievable by a combination of air photo interpretation, GIS analysis, and limited field verification. In high snow supply areas, it is appropriate for the qualified registered professional to incorporate a more detailed avalanche assessment at the block level as a part of a terrain stability field assessment.

During the harvest period, forest licensees or their contractors are required by law to take responsibility for avalanche hazards encountered during the winter and spring period. See Occupational Health and Safety Regulations 26.17 and 26.18 (Appendix 1).

With sound risk management policies, management commitment, staff training, and safe work procedures in place, avalanche risk can be managed successfully in winter operations (Figure 79).

At present it is not clear who owns the longer-term avalanche risk posed to downslope resources and facilities, especially in relation to logging on private land in British Columbia (Figure 80). The avalanche risk typically lasts for two or more decades until regrowth is sufficiently tall and dense to reduce the susceptibility of the area to generating large slab avalanches. In most forest tenures, the licensee's responsibility ends when the plantation becomes "free growing," which occurs well before avalanche susceptibility returns to preharvest levels. In a few cases, soil erosion by snow avalanches may mean that a forest will be very slow to regrow on newly formed avalanche paths and that the avalanche risk may endure for several decades.

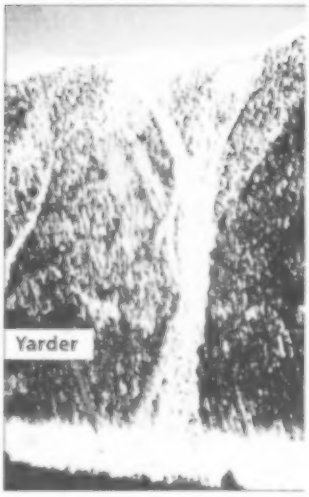


FIGURE 79
Managing the avalanche risk at a logging operation at Doctor Creek, southeast B.C. A yarder is working in the runout zone of a series of steep avalanche paths to winter harvest a block immediately below the photographer. Workers were trained in avalanche safety and rescue, and safe work procedures were implemented. Daily weather and avalanche observations were made and twice-weekly snow profile studies undertaken. Explosives used under controlled conditions triggered three avalanches (Size 1 and 2) from the large avalanche path above this work site.

3.4 LOGGING ABOVE HIGHWAYS

An interagency protocol, signed in 1992 by the B.C. Ministry of Transportation and Highways and B.C. Ministry of Forests, exists to minimize instances of increased snow avalanche risk posed to users of highways and transportation corridors in the province (Figures 81–83).

Under the protocol agreement, the Ministry of Forests is obliged to identify proposed cutblocks with the potential to generate avalanches that may reach a highway. In addition, the ministry is obligated to consult with the Ministry of Transportation over the licensee's Forest Development Plan and Logging Plan.

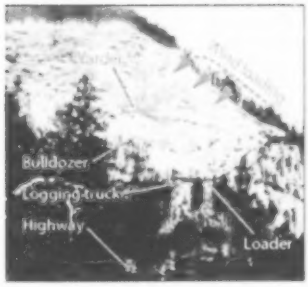


FIGURE 80 *Winter operations in potential avalanche terrain on private land at Enterprise Creek, Slocan Valley. The gully in which the yarder is working is likely to be subject to snow loading by the prevailing wind and may be prone to avalanching. Workers in the area may be at considerable risk unless daily snow stability evaluations are undertaken and safe work procedures are adopted. Avalanches from this path may pose a hazard to the travelling public on the highway below for two or three decades following harvest.*

FIGURE 82 *Avalanches initiating in the steep harvested terrain above the Trans-Canada Highway in the Kicking Horse Canyon have the potential to affect the highway even though the area is not often subject to deep snowpacks.*

FIGURE 81 *Steep terrain in a recently harvested cutblock on private land above Enterprise Creek may produce avalanches that run onto Highway 6. Who owns the risk?*

Risk Management Objectives

To minimize risk, the potential for logged slopes to avalanche must be addressed when planning a timber harvest.

The following benchmarks are offered as risk management objectives. The objectives acknowledge that there is residual risk associated with avalanche forecasting and control. The objectives are not intended to replace Workers' Compensation Board regulations (Appendix 1), which require due diligence and a high standard of care.

1. ***Workers on foot should not be put at risk of being involved with avalanches that could cause burial or injury.***

Objective: ***No avalanches greater than Size 1.5.***

2. ***Workers in trucks, industrial, or maintenance equipment should not be put at risk of being involved with avalanches that could damage a pick-up truck.***

Objective: ***No avalanches greater than Size 2.5.***

3. ***Avalanches of any size, resulting from explosive-based avalanche control should never run out onto a forest road or highway that is open to the public or industrial traffic, or onto occupied land.***

4. ***Avalanches triggered with explosives should, at most, cause only minimal damage to trees or minimal soil loss in or below any cutblock.***

Objective: ***No avalanches greater than Size 2.5.***

Note: No objective can be set for consequences of avalanche control undertaken in existing paths where natural avalanches have previously affected the forest.

These objectives were developed in consultation with participants of a workshop held in Revelstoke on March 16, 2000. Refer to Table 4 for details of the Canadian avalanche size classification system.

Two criteria are defined in the protocol by the Ministry of Transportation's Snow Avalanche Program:

- Maximum winter snowpack is greater than 0.5 m (a return period is not defined)
- Sighted angle from road to the top of block is greater than 25° (47%)

Foresters and consultants who undertake harvest planning and cutblock layout work in avalanche-prone terrain above highways or other facilities should consider the protocol methodology (Figure 84). An algorithm can readily be implemented in a geographic information system to identify potential areas of concern above public highways, railways, power transmission lines, or inhabited areas. A qualified registered professional should undertake on-site avalanche assessment and calculate the avalanche runout potential as a part of a detailed Terrain Stability Field Assessment for proposed cutblocks. A risk analysis should be undertaken for cutblocks that have the potential to reach the highway (see Table 13). The analysis should consider the exposure and vulnerability of persons or facilities.

FIGURE 83 *Harvesting was proposed in an even-aged pine forest along Highway 3 west of Castlegar, where red trees indicate insect attack. Inspection of the steep open talus slopes above the highway showed that avalanches impact the upper edge of the forest. Runout modelling indicated that avalanches initiating at the top of the steep open slopes and running on a smooth snow surface (e.g., where stumps and logging slash are buried by a deep winter snowpack) could reach the highway. Snow supply in the area is moderate. The south-facing aspect makes wet avalanches probable in spring. A risk analysis was undertaken to estimate the likelihood and expected frequency with which avalanches might reach the road edge. Mitigative measures proposed included retention of a timber buffer. Foresters then had to evaluate the potential for retained trees to succumb to insect attack.*

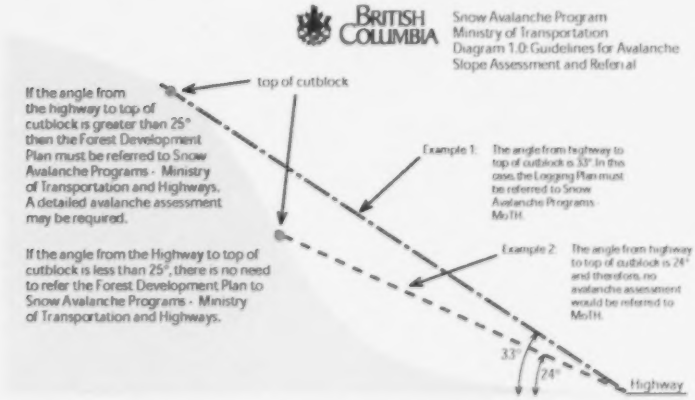

BRITISH COLUMBIA
Snow Avalanche Program
Ministry of Transportation
Diagram 1.0: Guidelines for Avalanche Slope Assessment and Referral
top of cutblock
If the angle from the highway to top of cutblock is greater than 25° then the Forest Development Plan must be referred to Snow Avalanche Programs - Ministry of Transportation and Highways. A detailed avalanche assessment may be required.
If the angle from the Highway to top of cutblock is less than 25°, there is no need to refer the Forest Development Plan to Snow Avalanche Programs - Ministry of Transportation and Highways.
Example 1: The angle from highway to top of cutblock is 33°. In this case, the Logging Plan must be referred to Snow Avalanche Programs - MoTH.
Example 2: The angle from highway to top of cutblock is 24° and therefore, no avalanche assessment would be referred to MoTH.
33°
24°
Highway

FIGURE 84 *Method used by MoF and MoT to identify proposed harvest blocks that may generate snow avalanches that could run out on public highways (25° = 47%). (Note: Protocol may be subject to revision. The term "logging plan" is now obsolete; the Forest Development Plan should be referred to the Ministry of Transportation.)*

TABLE 16 *Mapping methods that may be applicable for use in snow avalanche-prone terrain (after Gerath et al. 1996)*

	Name	Example	Strengths and weaknesses of method
A	Event Distribution Analysis	Avalanche atlas (Fitzharris and Owens 1983)	• Objective and qualitative • Creates a useful database of existing avalanche paths • Does not predict likelihood of new start zones being formed in harvested terrain
B	Event Activity Analysis	Inventory map drawn from a series of old air photos or from avalanche observation database	• Objective and qualitative • Creates a useful database of avalanche paths. Documents activity at different time periods • Does not predict likelihood of new paths being formed in harvested terrain
C	Event Density Analysis	Mapping of paths per unit land area (km^2); "susceptibility" mapping	• Objective and qualitative • Creates a useful database of avalanche paths. Some predictive value • Does not account for snow supply gradients caused by orographic enhancement of precipitation
D	Subjective Geomorphic Analysis	Polygon-based mapping; interpretation of slope, elevation, aspect, land form and length of fetch; French "Probable avalanche location" maps (Borrel 1992)	• Subjective, qualitative, and flexible • Terrain stability/avalanche hazard class criteria are often unspecified • Requires expert skill and judgement • Creates a useful database of avalanche paths and some terrain attributes • Difficult to review
E	Subjective Rating Analysis	Likelihood mapping; Hazard rating algorithms are developed for local areas and applied via GIS (Kelly et al. 1997)	• Subjective and qualitative to semi-quantitative. Flexible • Specified terrain stability/avalanche hazard classification criteria are often unspecified • Requires skill and judgement of an avalanche expert • Work can be delegated and checked. • Creates a useful database of many relevant terrain attributes • May present danger of over-simplification
F	Relative Univariate Analysis	Mapping based on statistically significant correlation of slope angle with avalanche occurrence	• Objective and qualitative to semi-quantitative • Relatively statistically based • Shows effect of individual terrain attributes • Data- and analytically intensive • Relies on quality data

Two criteria are defined in the protocol by the Ministry of Transportation's Snow Avalanche Program:

- Maximum winter snowpack is greater than 0.5 m (a return period is not defined)
- Sighted angle from road to the top of block is greater than 25° (47%)

Foresters and consultants who undertake harvest planning and cutblock layout work in avalanche-prone terrain above highways or other facilities should consider the protocol methodology (Figure 84). An algorithm can readily be implemented in a geographic information system to identify potential areas of concern above public highways, railways, power transmission lines, or inhabited areas. A qualified registered professional should undertake on-site avalanche assessment and calculate the avalanche runout potential as a part of a detailed Terrain Stability Field Assessment for proposed cutblocks. A risk analysis should be undertaken for cutblocks that have the potential to reach the highway (see Table 13). The analysis should consider the exposure and vulnerability of persons or facilities.

FIGURE 83 *Harvesting was proposed in an even-aged pine forest along Highway 3 west of Castlegar, where red trees indicate insect attack. Inspection of the steep open talus slopes above the highway showed that avalanches impact the upper edge of the forest. Runout modelling indicated that avalanches initiating at the top of the steep open slopes and running on a smooth snow surface (e.g., where stumps and logging slash are buried by a deep winter snowpack) could reach the highway. Snow supply in the area is moderate. The south-facing aspect makes wet avalanches probable in spring. A risk analysis was undertaken to estimate the likelihood and expected frequency with which avalanches might reach the road edge. Mitigative measures proposed included retention of a timber buffer. Foresters then had to evaluate the potential for retained trees to succumb to insect attack.*

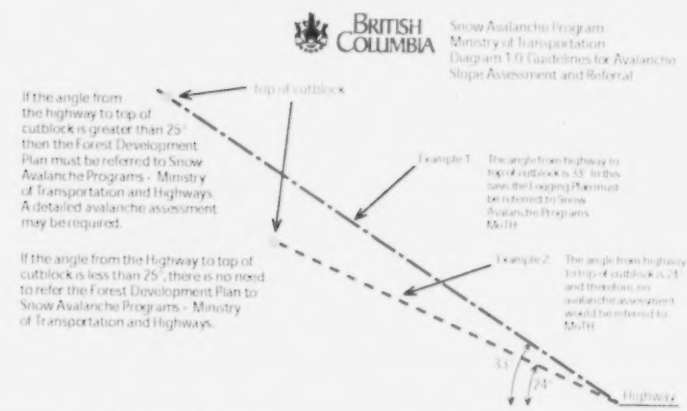

BRITISH COLUMBIA
Snow Avalanche Program
Ministry of Transportation
Diagram T.O. Guidelines for Avalanche Slope Assessment and Referral
If the angle from the highway to top of cutblock is greater than 25° then the Forest Development Plan must be referred to Snow Avalanche Programs - Ministry of Transportation and Highways. A detailed avalanche assessment may be required.
If the angle from the Highway to top of cutblock is less than 25°, there is no need to refer the Forest Development Plan to Snow Avalanche Programs - Ministry of Transportation and Highways.
Top of cutblock
Example 1
The angle from highway to top of cutblock is 33°. In this case the Logging Plan must be referred to Snow Avalanche Programs MoTH
Example 2
The angle from highway to top of cutblock is 24° and therefore, no avalanche assessment would be referred to MoTH
33°
24°
Highway

FIGURE 84 *Method used by MoF and MoT to identify proposed harvest blocks that may generate snow avalanches that could run out on public highways (25° = 47%). (Note: Protocol may be subject to revision. The term "logging plan" is now obsolete; the Forest Development Plan should be referred to the Ministry of Transportation.)*

TABLE 16 *Mapping methods that may be applicable for use in snow avalanche-prone terrain (after Gerath et al. 1996)*

	Name	Example	Strengths and weaknesses of method
A	Event Distribution Analysis	Avalanche atlas (Fitzharris and Owens 1983)	• Objective and qualitative • Creates a useful database of existing avalanche paths • Does not predict likelihood of new start zones being formed in harvested terrain
B	Event Activity Analysis	Inventory map drawn from a series of old air photos or from avalanche observation database	• Objective and qualitative • Creates a useful database of avalanche paths. Documents activity at different time periods • Does not predict likelihood of new paths being formed in harvested terrain
C	Event Density Analysis	Mapping of paths per unit land area (km^2); "susceptibility" mapping	• Objective and qualitative • Creates a useful database of avalanche paths. Some predictive value • Does not account for snow supply gradients caused by orographic enhancement of precipitation
D	Subjective Geomorphic Analysis	Polygon-based mapping; interpretation of slope, elevation, aspect, land form and length of fetch; French "Probable avalanche location" maps (Borrel 1992)	• Subjective, qualitative, and flexible • Terrain stability/avalanche hazard class criteria are often unspecified • Requires expert skill and judgement • Creates a useful database of avalanche paths and some terrain attributes • Difficult to review
E	Subjective Rating Analysis	Likelihood mapping; Hazard rating algorithms are developed for local areas and applied via GIS (Kelly et al. 1997)	• Subjective and qualitative to semi-quantitative. Flexible • Specified terrain stability/avalanche hazard classification criteria are often unspecified • Requires skill and judgement of an avalanche expert • Work can be delegated and checked. • Creates a useful database of many relevant terrain attributes • May present danger of over-simplification
F	Relative Univariate Analysis	Mapping based on statistically significant correlation of slope angle with avalanche occurrence	• Objective and qualitative to semi-quantitative • Relatively statistically based • Shows effect of individual terrain attributes • Data- and analytically intensive • Relies on quality data

	Name	Example	Strengths and weaknesses of method
A	Event Distribution Analysis	Avalanche atlas (Fitzharris and Owens 1983)	• Objective and qualitative • Creates a useful database of existing avalanche paths • Does not predict likelihood of new start zones being formed in harvested terrain
B	Event Activity Analysis	Inventory map drawn from a series of old air photos or from avalanche observation database	• Objective and qualitative • Creates a useful database of avalanche paths. Documents activity at different time periods • Does not predict likelihood of new paths being formed in harvested terrain
C	Event Density Analysis	Mapping of paths per unit land area (km^2); "susceptibility" mapping	• Objective and qualitative • Creates a useful database of avalanche paths. Some predictive value • Does not account for snow supply gradients caused by orographic enhancement of precipitation
D	Subjective Geomorphic Analysis	Polygon based mapping; interpretation of slope elevation, aspect, land form and length of fetch; French "Probable avalanche location" maps (Borrel 1992)	• Subjective, qualitative, and flexible • Terrain stability/avalanche hazard class criteria are often unspecified • Requires expert skill and judgement • Creates a useful database of avalanche paths and some terrain attributes • Difficult to review
E	Subjective Rating Analysis	Likelihood mapping; Hazard rating algorithms are developed for local areas and applied via GIS (Kelly et al. 1997)	• Subjective and qualitative to semi-quantitative. Flexible • Specified terrain stability/avalanche hazard classification criteria are often unspecified • Requires skill and judgement of an avalanche expert • Work can be delegated and checked • Creates a useful database of many relevant terrain attributes • May present danger of over-simplification
F	Relative Univariate Analysis	Mapping based on statistically significant correlation of slope angle with avalanche occurrence	• Objective and qualitative to semi-quantitative • Relatively statistically based • Shows effect of individual terrain attributes • Data- and analytically intensive • Relies on quality data

	Name	Example	Strengths and weaknesses of method
G	Probabilistic Univariate Analysis	No known examples	• Objective and quantitative • Probabilistic, statistically based • Simple to implement and test • Danger of selection of wrong terrain attributes • Data- and analytically intensive • Relies on quality data
H	Probabilistic Multivariate Analysis	Mapping based on statistically significant correlation of several terrain variables (slope angle, elevation, aspect) with avalanche occurrence	• Objective, and quantitative, precise • Probabilistic, statistically based • Danger of selection of wrong terrain attributes • Removes experience and judgement of mapper • Relies on high-quality data • Analytically intensive
I	Slope Stability Analysis	Stochastic modelling using Monte Carlo simulations; factor of safety approach (Conway and Wilbour 1999; Conway et al. 2000)	• Objective, and quantitative, precise • Can be reviewed • Difficult to use for mapping a large area • Shows influence of terrain attributes • Requires precise estimates of slope geometry, snow strength properties, and weather conditions • May not be process driven • Danger of oversimplification
J	Hazard Consequence	Consequence mapping	• Subjective and qualitative • Simple, no separate mapping required • Runout characteristics not mapped
K	Runout Zone	Swiss (red, blue, yellow, white) zoning maps; Icelandic risk maps (Keylock et al. 1999)	• Method can be subjective or objective, qualitative, semi-quantitative, or quantitative • Simple to complex delineation of risk zones • Practical for planning decisions
L	Linear Path Movement	Norwegian Geotechnical Institute mapping (Lied et al. 1989)	• Subjective and qualitative • Suited to linear movement • Field-intensive and analytically intensive • Relies on quality data
M	Linear Risk Mapping	Highway avalanche risk map (McClung and Navin 2002)	• Suited to linear transportation corridors • Field-intensive and analytically intensive • Relies on quality data

TABLE 16 *Continued*

	Name	Example	Strengths and weaknesses of method
G	Probabilistic Univariate Analysis	No known examples	• Objective and quantitative • Probabilistic–statistically based • Simple to implement and test • Danger of selection of wrong terrain attributes • Data- and analytically intensive • Relies on quality data
H	Probabilistic Multivariate Analysis	Mapping based on statistically significant correlation of several terrain variables (slope angle, elevation, aspect) with avalanche occurrence	• Objective, and quantitative, precise • Probabilistic–statistically based • Danger of selection of wrong terrain attributes • Removes experience and judgement of mapper • Relies on high-quality data • Analytically intensive
I	Slope Stability Analysis	Stochastic modelling using Monte Carlo simulations; factor of safety approach (Conway and Wilbour 1999; Conway et al. 2000)	• Objective, and quantitative, precise • Can be reviewed • Difficult to use for mapping a large area • Shows influence of terrain attributes • Requires precise estimates of slope geometry, snow strength properties, and weather conditions • May not be process driven • Danger of oversimplification
J	Hazard Consequence	Consequence mapping	• Subjective and qualitative • Simple; no separate mapping required • Runout characteristics not mapped
K	Runout Zone	Swiss (red, blue, yellow, white) zoning maps; Icelandic risk maps, (Keylock et al. 1999)	• Method can be subjective or objective, qualitative, semi-quantitative, or quantitative • Simple to complex delineation of risk zones • Practical for planning decisions
L	Linear Path Movement	Norwegian Geotechnical Institute mapping (Lied et al. 1989)	• Subjective and qualitative • Suited to linear movement • Field-intensive and analytically intensive • Relies on quality data
M	Linear Risk Mapping	Highway avalanche risk map (McClung and Navin 2002)	• Suited to linear transportation corridors • Field-intensive and analytically intensive • Relies on quality data

Where the slope within the proposed block is less than 25° (47%), the likelihood of avalanche initiation may be low or very low, though the likelihood rises rapidly for slopes above 30° (58%). Alternatives to large clearcuts may be appropriate in higher-risk situations. In some cases, the risk to life and limb or potential liability may be too great.

3.5 AVALANCHE MAPPING

Mapping of existing avalanche paths is useful for identifying risks to worker safety, especially on winter access roads. Mapping of areas that have the potential to generate avalanches following timber removal is a much more difficult task.

Identifying avalanche-prone terrain is a strategic tool for assessing the long-term risk following forest harvesting. At present, there is no widely accepted method of mapping post-harvest avalanche risk. The following discussion gives some ideas of possible approaches (see Table 16).

The Ministry of Forests inventory mapping of environmentally sensitive areas (ESAs) includes snow avalanche susceptibility (ESA-Ea). In practice, ESA mapping for avalanche risk is seldom used and has not been applied consistently across the province (P. Jordan, MoF, pers. comm.). The British Columbia terrain classification system presents a classification and a single on-site symbol for snow avalanches (Howes and Kenk 1998) (Appendix 6). To date, most avalanche mapping undertaken in the province's forests relates to geomorphic processes as opposed to avalanche susceptibility or risk.

No agreed standard has been set for avalanche susceptibility mapping within the province, a situation similar to that existing for terrain mapping in the 1980s. By contrast, European cartographers have developed a broad range of mapping symbols (e.g., Borrel 1992; Lambert 1992).

Mappers and forest managers should review the merits of the various methods listed in Table 16 before initiating major projects. Management objectives, expectations, and outcomes should be carefully defined before mapping is undertaken. Mapping of existing avalanche paths is straightforward; the challenge is to map the terrain factors that might become start zones if the forest were removed.

Air Photo Interpretation

Oblique colour photographs taken in the spring from fixed-wing aircraft or helicopters are very useful at the start of an investigation into avalanche activity in an area. Active start zones may become bare much earlier than adjacent slopes of similar aspect because much of the snowpack may be removed by avalanching. By contrast, avalanche deposits may remain in the valley floor and gullies long after the snowline has receded up a mountain or melted from all but high-elevation, shaded alpine cirques and plateaus.

Avalanche mapping projects generally begin with the stereoscopic interpretation of vertical air photographs and with the study of topographic maps (Figure 85). The air photo interpreter should have experience in identifying avalanche start zones and tracks in the field and have an understanding of the processes involved in the formation and motion of avalanches. Inferences made during air photo interpretation should be

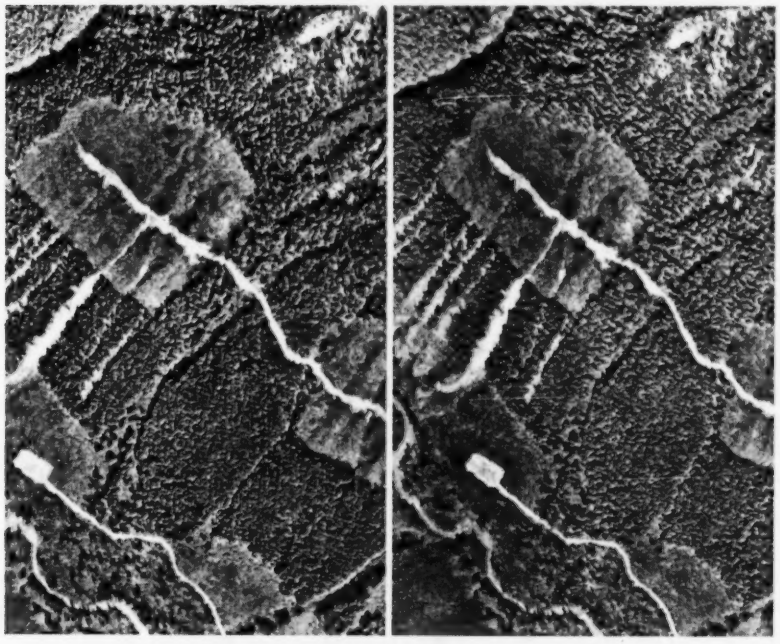


FIGURE 85 *Stereopair of Nagle Creek avalanche path. A low-power pocket stereoscope is required to see the terrain in three dimensions. Scale approximately 1:15 000 (Airphotos 30 BCB97061 nos. 272 and 273).*

verified in the field. Conclusions should be reached only after one has taken into account a combination of clues and considered the interactions of terrain and vegetation.

Use of air photos at a scale slightly larger than that of the finished map is preferred. Small-scale photos from high-level flights (scale between 1:25 000 and 1:80 000) allow the identification of paths in avalanche-prone areas and the study of complete individual paths. Large-scale photos taken from low-level flights (scale between 1:10 000 and 1:25 000) are best suited for detailed study of avalanche start zones, tracks, and runout zones. Air photos are usually taken late in the summer when the area of interest is free of snow. Colour photos are helpful when available, but black-and-white photos are satisfactory.

Small-scale Terrain Features

The forest cover on air photos often conceals many small-scale terrain features.

Air photo interpretation of potential avalanche terrain under a forest cover is unlikely to reveal the details of the steepness of the terrain, the slope breaks, the shallow gullies, the rock bluffs, and surface roughness. These detailed terrain features may contribute to generating potential avalanches once the forest cover is removed, and should be assessed in the field.

Examining older, monochrome, vertical air photos (if available), can give interpreters an appreciation of the growth and age of the forest in avalanche paths, which in turn can lead to inferences about the frequency of major avalanche occurrences and/or the degree of vegetative recovery.

Avalanches that initiate in the alpine zones but descend through the forest are usually obvious. Avalanche start zones located within the forest cover are less distinct. However, subtle changes in the height, grey tone or colour, and density of the trees or other vegetative features can provide good clues to experienced air photo interpreters. Short paths, where avalanches may initiate from over-steepened road cut-banks or in small shallow channels, may not be identifiable on large-scale vertical air photos.

Field Checking

Air photo interpretations and mapping should be field verified at an appropriate terrain survey intensity level. The *Mapping and Assessing Terrain Stability Guidebook* (B.C. Ministry of Forests 1999) discusses terrain survey intensity level in relation to map scale. For 1:5000 to 1:10 000 scale mapping projects, Ryder (2002) recommends ground checking 75–100% of terrain polygons. For these scales, terrain polygons will be in the order of 2–5 and 5–10 ha, respectively.

Ortho-rectified, monochrome air photos (orthophotos), overlain with the B.C. 1:20 000 scale Terrain Resource Inventory Map (TRIM) digital contour data, can be used very effectively with a planimeter and scale rule to determine start zone and runout zone areas, slope angles, and lengths of avalanche track. Avalanche paths outlined on orthophotos can be digitized and the underlying TRIM data used to plot longitudinal profiles and to calculate areas (Figure 86).

Orthophotos overlain with TRIM contours, enlarged to 1:10 000 or 1:5000 scale, are useful for marking positions and noting the location of small gullies and other features. However, such mapping is no more accurate than 1:20 000 TRIM; it is simply easier to use in the field.

During field inspection, a detailed road survey should be undertaken. It should focus on specific features such as steep cutbanks, over-steepened fillslopes, rock bluffs, gully or other channel crossings,

Map Scale

It is important to recognize the limitations of information portrayed on maps in relation to scale. For example, 1:20 000 TRIM data often fail to show local scale features such as steep gullies, rock bluffs, and road cutslopes. Topographic mapping at 1:5000 scale should be commissioned when working in high-consequence areas.

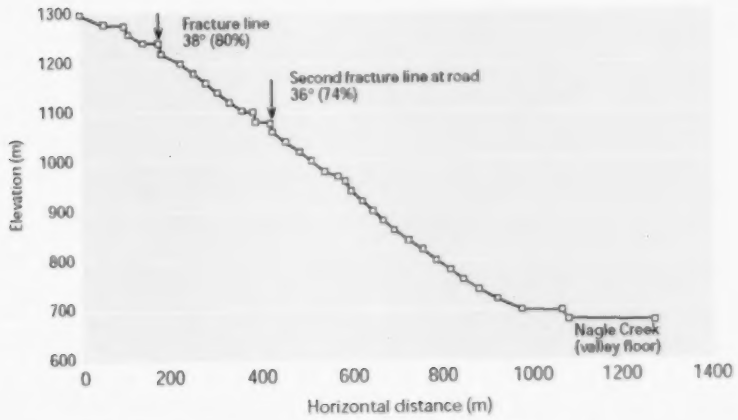


FIGURE 86 *Slope profile of the Nagle Creek avalanche path plotted from 20-m TRIM contours.*

and existing avalanche path crossings. The road distance (kilometre) position of these important features should also be noted. The location of the road with respect to the cutblock (e.g., whether the road traverses the top, centre, or bottom of steep cutblocks). A pocket stereoscope and air photo stereopairs should be taken into the field for reference and corroboration.

The Canadian Avalanche Association's *Guidelines for Avalanche Risk Determination and Mapping in Canada* (McClung et al. 2002) and a Joint Practice Board skillset for snow avalanche assessments (JPB 2002) presents guidance for qualified registered professionals carrying out Terrain Stability Field Assessments in snow avalanche-prone terrain.

Avalanche Mapping for Land Use Planning

Switzerland

In Switzerland, where the observational record of avalanche activity spans many centuries, avalanche mapping incorporates a zoning based on a calculation of impact pressure and an estimate of return period. These are:

- High hazard (Red) zone—an area where impact pressures are greater than 30 kPa, with an annual exceedance probability of up to 1 in 300; or any area likely to be affected by any avalanche with an annual exceedance probability of more than 1 in 30. New buildings and winter parking are prohibited. Existing buildings must be protected and evacuation plans prepared.
- Moderate hazard (Blue) zone—areas affected by flowing avalanches where the maximum impact pressure is less than 30 kPa, with an annual exceedance probability of 1 in 30 to 1 in 300, or any area likely to be affected by powder avalanches with impact pressures less than 3 kPa. Public buildings where people may gather should not be constructed. Special engineering designs are required for private residences. The area may be closed during periods of avalanche danger. Evacuation plans must be prepared.
- Low hazard (Yellow) zone—an area where flowing avalanches are possible, with an annual exceedance probability of less than 1 in 300 (i.e., rare); any area likely to be affected by powder avalanches with impact pressures of less than 3 kPa with an annual exceedance probability of less than 1 in 30. Structural defence measures may be recommended.
- No hazard (White) zone—an area where there are no building restrictions.

Gruber and Bartelt (2000) describe how the Swiss zoning system performed when tested by the severe European winter of 1999. Deficiencies in the delineation of Yellow zones were noted and attributed to the under-estimation of runout distances.

Norway

The Norwegian Geotechnical Institute (NGI) has undertaken overview mapping of avalanche areas (on 1:50 000 scale, 20-m contour interval base maps) using computer digital terrain modelling techniques (Lied et al. 1989). Potential start zones are identified as areas steeper than 30° (58%) and not covered in dense forest. Potential avalanche trajectories are drawn downslope from previously identified start zones by an operator at a computer workstation. The system computes a longitudinal profile, then calculates the maximum probable avalanche runout distance based on the alpha and beta angle (α and β) slope profile analysis method (Lied and Toppe 1989; see Figure 30).

All NGI maps are checked against stereopairs of vertical air photographs to verify the reasonableness of the modelled runout. The maps are then field-checked. The maps do not contain any information on avalanche frequency. No distinction is made between avalanche paths that run once in 100 years and those that may run annually. (Note: Use of the alpha-beta model implies an annual probability of 1:100.)

The NGI notes that the use of 20-m contour base mapping creates an inherent weakness (in common with TRIM map data) in that locally steep slopes with a vertical interval of up to 20 m may not be identified.

France

In France, mapping of "probable avalanche paths" is undertaken at scale of 1:25 000 (Borrel 1992; Furdada et al. 1995). Conventional avalanche maps produced by a combination of fieldwork and air photo interpretation have been integrated with digital terrain modelling analysis of avalanche runout using the NGI's techniques. The French maps display the expected maximum runout, but do not contain information on impact pressure or frequency (Figure 87).

Note: Avalanche mapping systems are currently under review in several European countries, as large avalanches have overrun previously mapped runout boundaries. Recent avalanche disasters have occurred in both France and Austria (Lambert 2000).

FIGURE 87 *Avalanche mapping for Val d'Isère, France (scale 1:25 000). Mapping in orange is from air photo interpretation. Mapping in magenta is based on field surveys, interviews with local witnesses including Forest Service rangers, and ski patrollers. Solid cross-hatching implies more certainty than areas delineated with broken cross-hatching. (After Borrel 1992)*

New Zealand

Avalanche mapping has been completed on many high-use alpine hiking trails in New Zealand and on one tourist highway. Avalanche mapping was undertaken at 1:30 000 on a 28 km length of the Milford Road where 50 major avalanche paths plunge from alpine areas subject to very high precipitation (8000–10 000 mm/yr) through remnants of forest to a narrow valley floor (Fitzharris and Owens 1980).

For a time, the mapping undertaken along the route was considered by road authorities to over-estimate avalanche runout distances but a series of heavy winters in the mid-1990s, when additional areas of old forest were destroyed, proved the mapping to be conservative. No frequency was implied in the mapping, but estimates were given in an accompanying technical report. Active avalanche control undertaken above the highway in heavy winters increased the frequency of major avalanching on most paths by at least an order of magnitude above the estimates made by the mappers.

The mappers used the hazard index concept developed for British Columbia's highways (Schaerer 1989) for both the Milford Road and avalanche-prone walking tracks in New Zealand. Observational data have subsequently been reworked to estimate a "probability of death for an individual" (PDI) traversing the road (Weir 1998).

Iceland

Mapping undertaken above a village in Iceland represents one of the first applications of risk-based mapping to snow avalanches (Keylock et al. 1999). Vulnerability of the village inhabitants was assessed based on the construction of the dwellings (reinforced or non-reinforced). Risk contours, produced via simulation of extreme avalanche runout, were plotted across the runout zone and expressed as a PDI (Figure 88).

The critical difference between the risk mapping approach and the traditional Swiss method or other hazard line techniques is that risk is treated as a gradient, measured in terms of potential for loss of life. There is no indication of acceptability of risk in this method compared to the more traditional zoning systems.

United States

Vail, Colorado and Ketchum, Idaho have introduced land use planning ordinances based on avalanche influence zones modelled on the Swiss approach (Mears 1992). Land use restrictions are enforced.

Canada

Technical guidelines for avalanche risk determination and mapping in Canada have recently been prepared (McClung et al. 2002). The guidelines propose a risk-based land use zoning system, calculated as the product of avalanche return period and impact pressure. Training courses will be offered in association with the guidelines. Readers should check with the Canadian Avalanche Association or the B.C. Forestry Continuing Studies Network for course schedules.

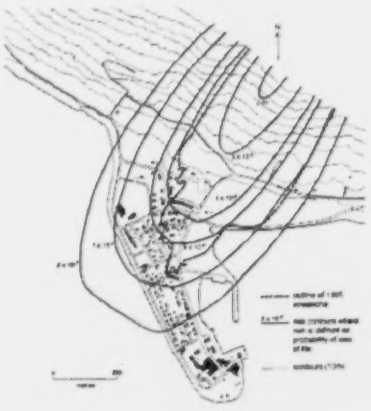


FIGURE 88 *Risk map produced by simulation of avalanche runout (based on probability of risk exceedance). Dotted line is extent of runout of an event in 1995 that occurred in Iceland. Solid contours map risk as probability of loss of life. (After Keylock et al. 1999)*

Highways in British Columbia

In British Columbia, the Ministry of Transportation's Snow Avalanche Program has mapped almost all avalanche-prone highways (Figure 25). Expert judgement, observational data, and air photo interpretation are used to make a best estimate of the likely avalanche runout on individual paths. Each path is shown on an oblique air photo and on a 1:50 000 scale strip map (Figure 89). The Ministry's avalanche atlases contain a table of expected avalanche frequency that is updated as more observational data become available (e.g., B.C. Ministry of Transportation and Highways 1991). Observational data from previous winters are available to avalanche technicians from a computer database.

The Ministry generally does not map maximum expected runout, because that is not of great importance in transportation planning. The length of road affected and proximity to other avalanche paths, in combination with likely vehicle speed and length, are more important than the runout distance, as these variables determine the exposure of a driver to avalanches.

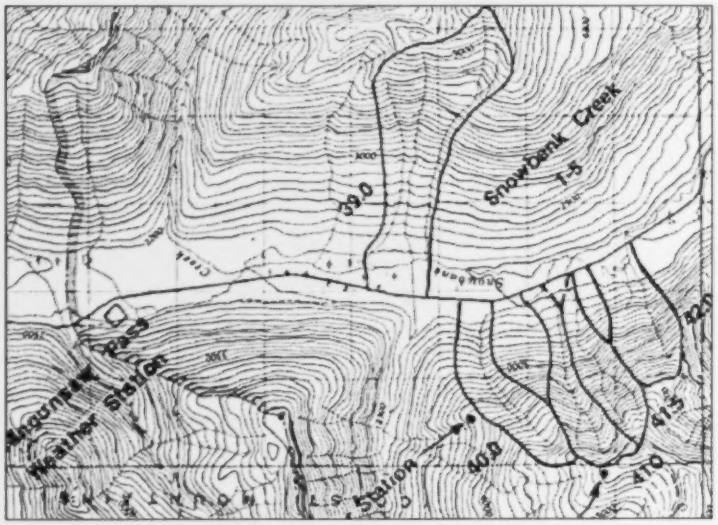


FIGURE 89 *Ministry of Transportation avalanche mapping showing distribution of avalanche paths above highway at Ningusaw Pass, between Bob Quinn Lake and Stewart, B.C. (scale: 1:78 125). (No indication of frequency or maximum runout distance implied.)*

Highways in British Columbia

In British Columbia, the Ministry of Transportation's Snow Avalanche Program has mapped almost all avalanche-prone highways (Figure 25). Expert judgement, observational data, and air photo interpretation are used to make a best estimate of the likely avalanche runout on individual paths. Each path is shown on an oblique air photo and on a 1:50 000 scale strip map (Figure 89). The Ministry's avalanche atlases contain a table of expected avalanche frequency that is updated as more observational data become available (e.g., B.C. Ministry of Transportation and Highways 1991). Observational data from previous winters are available to avalanche technicians from a computer database.

The Ministry generally does not map maximum expected runout, because that is not of great importance in transportation planning. The length of road affected and proximity to other avalanche paths, in combination with likely vehicle speed and length, are more important than the runout distance, as these variables determine the exposure of a driver to avalanches.

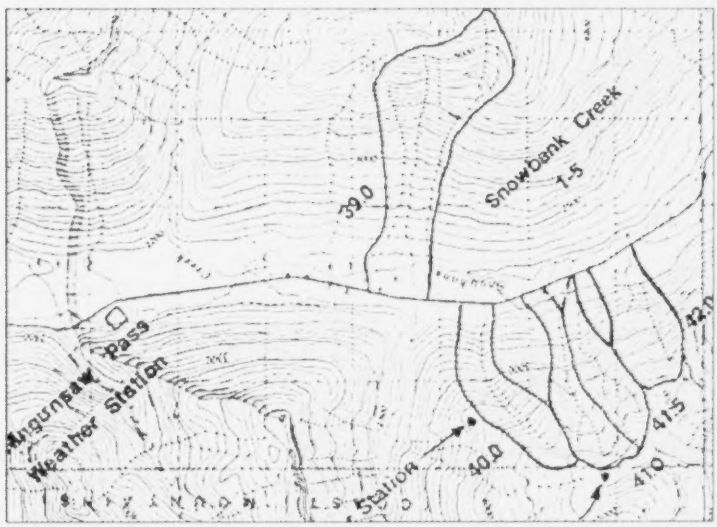


FIGURE 89 *Ministry of Transportation avalanche mapping showing distribution of avalanche paths above highway at Ningusaw Pass, between Bob Quinn Lake and Stewart, B.C. (scale: 1:78 125). (No indication of frequency or maximum runout distance implied.)*

The Ministry has responsibility for approving access to subdivisions in unincorporated areas in British Columbia.; snow avalanches are one of a number of slope hazards considered in the approval process. The Snow Avalanche Program has defined a "hazard line" in Stewart, B.C. to delineate a boundary for potential avalanche influence from Mt. Rainey. Evacuation of defined areas, including the log sort and port, may be implemented in extreme avalanche conditions.

Regional Districts in British Columbia

No common approach has been adopted for land use planning in the regional districts of British Columbia. A zoning system developed in the Fraser Valley Regional District employs hazard acceptance thresholds for dealing with snow avalanches and other natural hazards (Cave 1992). The Fraser Valley Regional District employs a matrix to prescribe responses to development applications for various types of projects on lands subject to snow avalanches for a range of annual exceedance probabilities (Table 17). The column headed "1:500–1:10 000" is considered redundant because it is impossible to distinguish between that class and the "1:100–1:500" return period class. The column headed "greater than 1:10 000" defines a non-restrictive response for areas where avalanche events have not and will not occur.

The Fraser Valley Regional District has applied the avalanche planning restriction to projects in the Hemlock Valley area where poorly restocked clearcuts, harvested in the 1960s, continue to pose an avalanche hazard to private land downslope. This example underscores the serious implications that may follow ill-considered clearcut logging on steep slopes that have the potential to run out into developed areas. The loss in value of potentially affected residential properties will often outweigh the value of the timber resource.

Because of the great destructive potential of avalanches and the dread associated with the phenomenon, the response of the Fraser Valley Regional District is essentially one of avoidance rather than mitigation. Interestingly, the planning response to floods, a more familiar hazard, is less restrictive.

TABLE 17 *Fraser Valley Regional District snow avalanche planning response (source: Cave 1992)*

	Snow avalanche expected return period				
Proposed project	< 1:30	1:30-1:100	1:100-1:500	1:500-1:10 000	> 1:10 000
Minor repair (< 25% value)	5	4	4	4	1
Major repair (> 25% value)	5	4	4	4	1
Reconstruction	5	4	4	4	1
New building	5	4	4	4	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

Hazard-related planning response:

1 Approval, without conditions relating to hazard.

2 Approval, without siting conditions or protective works, but with a covenant including a "save harmless" clause.

3 Approval, with siting requirements to avoid the hazard, or with requirements for protective works to mitigate the hazard.

4 Approval, as in (3) above, but with a covenant including a "save harmless" condition, as well as siting conditions, protective works, or both.

5 Not approvable.

Terrain Stability Mapping in British Columbia

Terrain stability mapping is a derivative process that draws on known attributes of surficial materials, landforms, slope steepness, and geomorphic processes within the natural landscape that control slope stability. Two types of terrain stability maps are undertaken to assist with forest management in British Columbia—detailed and reconnaissance maps. Reconnaissance terrain stability mapping uses air photo interpretation, but little field-checking, to delineate areas (polygons) of stable, potentially unstable, and unstable terrain within a particular landscape. By contrast, detailed terrain mapping involves a substantial field campaign to categorize, describe, and delineate landscape characteristics and to investigate active geomorphological processes. Detailed terrain stability mapping uses a five-class system (Class I to V) to rate stability following forest harvesting and road building. Ryder (2002) gives a complete discussion of the differences in the methods.

Existing snow avalanche paths are mapped with onsite symbols (arrows) and described in terrain polygons with the geomorphic process qualifier "-A" (see Appendix 6 and Figure 90). Rollerson et al. (2000) propose an extension to adopt the "-A" notation to indicate that the terrain may be avalanche-prone following harvesting.

Avalanche Mapping for the British Columbia Forest Sector

Topographic analysis using a GIS and a digital elevation model identify slopes between 30 and 50° (60–120 %) as a first pass in filtering terrain

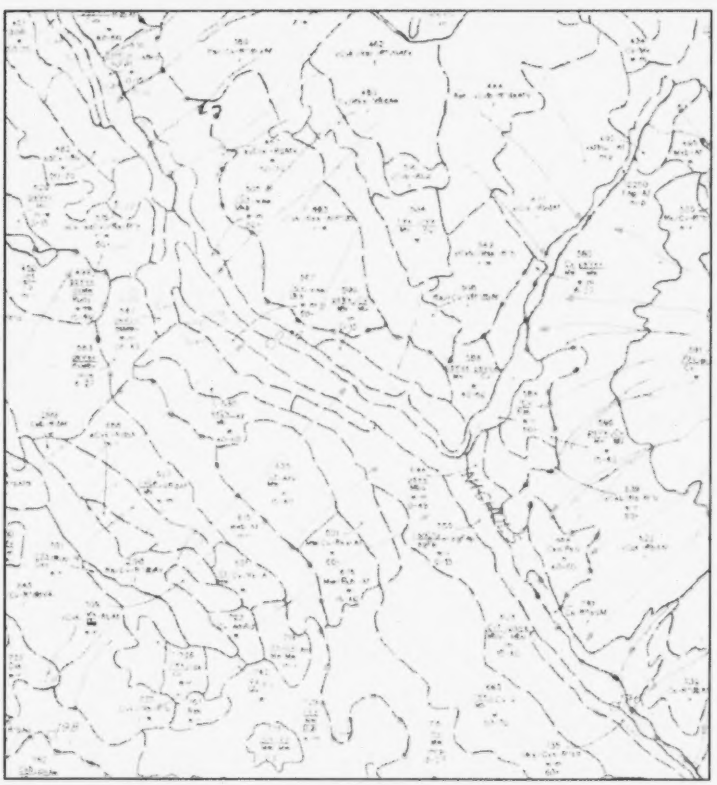


FIGURE 90 *Terrain mapping for an area in the Interior of British Columbia that has both major and minor avalanche paths (scale 1:20 000, TSIL C and E; TRIM map sheet 93J.084). Solid-head arrows indicate existing avalanche paths, small-headed arrows indicate landslide tracks. See Appendix 6 for details of terrain mapping legends that relate to snow avalanches. (Source: J.M. Ryder and Associates, Terrain Analysis Inc.)*

likely to generate snow avalanches, given an unstable snowpack and sufficient loading. Slope maps can be readily produced. Analytical techniques can be employed to identify convex slopes and gully systems where avalanches may initiate. Topographic exposure and the length of fetch from any upwind plateau or other topographic feature can be computed. This approach has been applied in the Revelstoke–Columbia Forest District by Kelly et al. (1997) in an effort to delineate areas with a moderate or high likelihood of avalanche initiation following clearcut harvesting.

The Canadian guidelines and standards for avalanche risk and hazard mapping give an example of a forestry risk zone map, which designates a protection forest above a highway (McClung et al. 2002).

Mapping and Acceptable Risk

Persons undertaking avalanche mapping should not attempt to define risk acceptability (as is implicit when a hazard line or zone boundary is drawn on a map). Instead, risk acceptability should be established by society through a consultative land use planning process based on informed debate (the Land and Resource Management Planning process may offer a suitable model). Consultation should take place in an environment of open risk communication (Canadian Standards Association 1997). Risk mapping provides a good tool to promote open communication.

Map Use and Interpretation

It is important that avalanche maps contain a detailed explanation of the methods used to establish avalanche likelihood and risk. The accuracy, reliability, and limitations of data should be defined. As with terrain stability maps, a detailed technical report should accompany any avalanche map. That report should include a risk assessment, conclusions, and recommended mitigations (CAA 2002).

Gerath et al. (1996) note that unless users of quantitative risk assessments understand the limitations of the methods and consider the data employed then they may be misguided by the apparent precision provided by the numbers presented. Conversely, a drawback to using a qualitative rating is that terms such as "low," "medium," and "high" mean different things to different people, and hence map users may interpret meanings other than those intended by the mapper.

3.6 DOCUMENTING EXISTING AVALANCHE PATHS

Licensees operating in moderate- or high-risk areas may wish to document all recognized avalanche paths in an avalanche atlas. Each path should be plotted on an oblique aerial photograph and on a topographic base map (preferably 1:20 000 scale or larger). Basic terrain features can be analyzed by map interpretation or digital terrain modelling, but should be confirmed by field inspection.

An overview map displaying all identified paths in the area should be presented, along with a summary of climate and snowfall records. An analysis of the avalanche risk should also be provided (Fitzharris and Owens 1980).

Figure 92 is excerpted from a B.C. Ministry of Transportation and Highways avalanche atlas for the Terrace area. The likely maximum affected area is outlined on an oblique photo of the area. Avalanche mapping undertaken for highway projects is generally not concerned with runout that extends below the road. Risk assessment considers the period of time that a vehicle will be exposed in the path (a function of road grade and vehicle type).

3.7 RUNOUT PREDICTION

Dynamics Modelling Approach

Avalanche runout modelling should be undertaken when some element located downslope of a proposed road or opening may be at risk from avalanches initiating in a forest opening (e.g., Figure 91).

The traditional approach to avalanche runout modelling is to survey the slope in question and use an avalanche dynamics model to predict the speed of the avalanche mass (Figure 93). The most commonly applied method employs the Perla, Cheng, and McClung model (PCM) or some derivative of it (Perla et al. 1980; Mears 1992). The PCM model can be coded in a programming language or implemented on a spreadsheet and the output graphed. Experience and expert judgement are used to select friction coefficients and to calibrate the modelled runout against

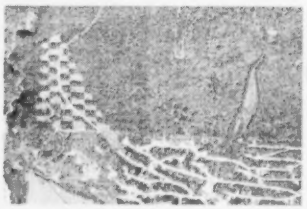


FIGURE 91 *A landslide initiating below an old road created an opening in the forest (outlined in red). A subdivision was subsequently developed in the landslide deposition zone. Residents have expressed concern about the potential for snow avalanches and further landslides (Kamloops Daily Sentinel, Sept. 15, 1976). Avalanche runout modelling can be employed to establish whether an avalanche initiating at the head of the landslide track might reach the subdivision (see Figure 93). In this instance, snow supply, likely avalanche size, and avalanche return period determine the risk. (Ross Creek area below Crowfoot Mountain; map sheets 82L 094 and 95)*

Shames #3 - Avalanche Path Summary

NAME	**Shames #3**	NUMBER: 12.9
LOCATION	On the Shames River road leading to Shames Ski Area. 12.9 km from the junction of Highway #16	
MAP	103 I / 7 W	
AERIAL PHOTOS	B.C. 7728: 213-214 (1:24 000)	

DESCRIPTION

ELEVATION: (metres above sea level) Start zone: 670 m Runout Zone: 365 m		Vertical Fall: 305 m
START ZONE AREA: 20 hectares		
START ZONE ASPECT: South-south-west		
SLOPE ANGLE: Start zone: 40°	Track: 30°	Runout Zone: Level
Beta Angle (β) *	Not specified	Measured angle from the (Beta) point where the path gradient falls to 10° up to the top of the start zone.
Distance to Beta point (X_β) *	Not specified	Measured horizontal distance from the top of the path to Beta point.
Start zone	A steep logged slope with numerous stumps and fallen timber. Locally oversteepened by road cut and fill.	
Track	A steep logged slope. The upper road crosses this slope and the lowest road is at the base of the slope.	
Runout Zone	Beyond the lowest road.	
Elements at Risk	Public travelling to ski area and industrial road users. No other facilities at risk.	
Comment	Length of public highway affected is 1000 m on the lower road and 800 m on the upper road. Good forest regeneration noted Feb. 2000.	

HISTORY:

	Total Recorded Avalanches	Recorded Avalanches on Highway	Recorded Average Depth on Highway (m)
1999-2000	0	0	
2000-2001	0	0	
TOTALS	0	0	

Notable Avalanche Occurrences:
No avalanche incidents have been recorded for this path.

* See Figure 94 and accompanying Section 3.7 on runout prediction for an explanation of beta angle and distance to beta point.

FIGURE 92 *Typical page from an avalanche atlas (after B.C. Ministry of Transportation and Highways Snow Avalanche Program 1991.)*

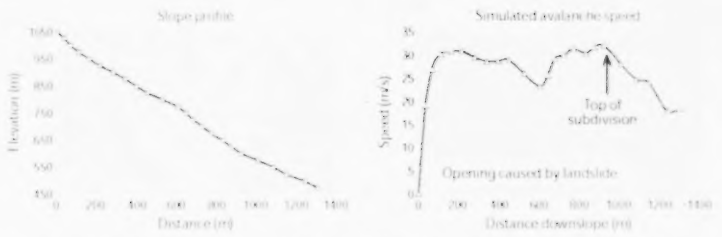


FIGURE 93 *Deterministic application of the PCM avalanche dynamics model to the area shown in Figure 91.*

- *Avalanche predicted to attain maximum speed of 30 m/s (110 km/h) within first 100 m of slope.*
- *A sensitivity analysis should be undertaken using a range of values for the friction coefficient (μ).*
- *Avalanche speed at the point of interest is critical for any estimate of likely impact pressure.*

known large events. Considerable research has been undertaken on this topic in Europe (Salm and Gubler 1985).

Deterministic versus Stochastic Modelling

Avalanche dynamics models are traditionally applied in a deterministic way, which yields a simplistic "yes or no" result to the problem of whether an avalanche will impact some point of interest (POI). In the discipline of landslide failure analysis, recent work is moving towards stochastic modelling, which yields a probability that a failure may occur (Hammond 1992; Wilkinson and Fannin 1997). Similarly, it is possible to run a Monte Carlo simulation, using a spreadsheet add-in application, to stochastically model avalanche runout via the dynamics approach.

The avalanche dynamics approach has been criticized because of the lack of objective criteria available for the selection of friction coefficients for paths and mountain ranges other than those where the original research was undertaken. Uncertainties about the mechanical properties of flowing snow and its interaction with terrain make this method speculative.

Probabilistic Modelling Approach

An alternative method for predicting extreme (100-year) avalanche runout based on simple terrain variables, originally proposed by the Norwegian Geotechnical Institute (NGI), has become the preferred method in North America for runout prediction (Lied and Toppe 1989). Terrain variables are used to specify an angle, alpha (α), which is defined by sighting from the point of extreme runout to the top of the start zone (Figure 94). Alpha angles can vary from 15 to 50° (27–120%) depending on the terrain (McClung and Mears 1991). The Ministry of Transportation–Ministry of Forests avalanche protocol employs an alpha angle of 25° (see Figure 94).

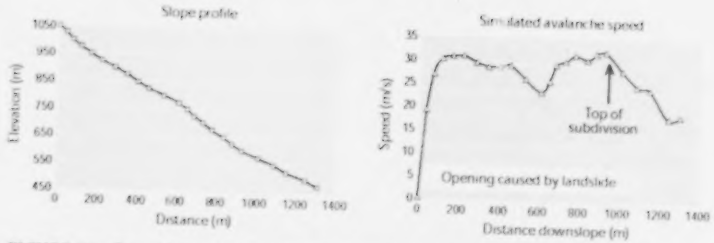


FIGURE 93 *Deterministic application of the PCM avalanche dynamics model to the area shown in Figure 91.*
- *Avalanche predicted to attain maximum speed of 30 m/s (110 km/h) within first 100 m of slope.*
- *A sensitivity analysis should be undertaken using a range of values for the friction coefficient (μ).*
- *Avalanche speed at the point of interest is critical for any estimate of likely impact pressure.*

known large events. Considerable research has been undertaken on this topic in Europe (Salm and Gubler 1985).

Deterministic versus Stochastic Modelling

Avalanche dynamics models are traditionally applied in a deterministic way, which yields a simplistic "yes or no" result to the problem of whether an avalanche will impact some point of interest (POI). In the discipline of landslide failure analysis, recent work is moving towards stochastic modelling, which yields a probability that a failure may occur (Hammond 1992; Wilkinson and Fannin 1997). Similarly, it is possible to run a Monte Carlo simulation, using a spreadsheet add-in application, to stochastically model avalanche runout via the dynamics approach.

The avalanche dynamics approach has been criticized because of the lack of objective criteria available for the selection of friction coefficients for paths and mountain ranges other than those where the original research was undertaken. Uncertainties about the mechanical properties of flowing snow and its interaction with terrain make this method speculative.

Probabilistic Modelling Approach

An alternative method for predicting extreme (100-year) avalanche runout based on simple terrain variables, originally proposed by the Norwegian Geotechnical Institute (NGI), has become the preferred method in North America for runout prediction (Lied and Toppe 1989). Terrain variables are used to specify an angle, alpha (α), which is defined by sighting from the point of extreme runout to the top of the start zone (Figure 94). Alpha angles can vary from 15 to 50° (27–120%) depending on the terrain (McClung and Mears 1991). The Ministry of Transportation–Ministry of Forests avalanche protocol employs an alpha angle of 25° (see Figure 94).

The NGI runout model assumes a parabolic slope profile. It should employ relationships established by regression analysis of data from the mountain range under study. Alternatively, the model can be calibrated against known extreme avalanche paths in the study area.

The return period of extreme avalanche runout may be modelled in space and time through application of extreme value statistics. McClung (2000) shows how Gumbel parameters used for runout modelling are related to climate and terrain.

The ratio of the horizontal distance that an avalanche runs beyond the beta point (Δ_x) to the horizontal distance from the start point to the beta point (X_β) is termed the "runout ratio" (Δ_x/X_β). This is considered to be a better predictor of runout distance than that based on regression of the alpha angle (α) (McClung et al. 1989). The method is applicable to small and truncated data sets, which makes it attractive for use in situations where detailed information on avalanche runout is limited.

The runout ratio can be fitted to an extreme value distribution (Gumbel distribution) to facilitate the prediction of high-frequency snow avalanches (Smith and McClung 1997; McClung 2001b) (Figure 94).

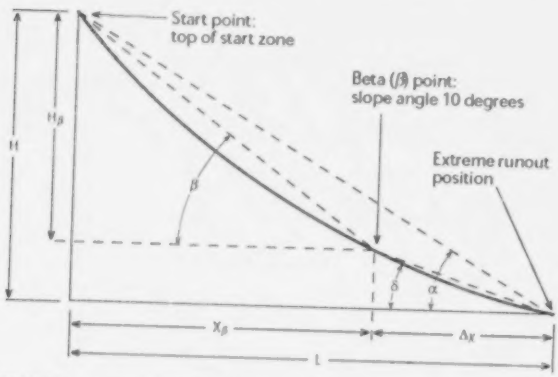


FIGURE 94 *Terrain parameters used in runout calculation:*

β *(beta) is the measured angle from the (beta) point where the path gradient falls to 10° up to the top of the start zone*

α *(alpha) is the predicted angle from the end of maximum runout to the top of the start zone*

δ *(delta) is the angle from the point of extreme runout to the beta point*

X_β *the measured horizontal distance from the top of the path to the beta point where the gradient first falls to 10°*

Δ_x *the predicted distance (m) between the beta point and the extreme runout position*

L *the horizontal distance from top of the path to the extreme runout point*

H *the total vertical fall (m)*

H_β *the vertical fall (m) from the top to the elevation of the beta point*

(After Lied and Toppe 1980; McClung and Mears 1991)

McClung and Mears (1991) define a runout ratio (Δ_x / X_β), a dimensionless measure of extreme avalanche runout, for the prediction of zones affected by high-frequency avalanching as:

$$\frac{\Delta_x}{X_\beta} = \frac{\tan\beta - \tan\alpha}{\tan\alpha - \tan\delta}$$

Tables 18 and 19 shows how extreme runout summary statistics vary with the terrain properties found in different mountain ranges (Smith and McClung 1997; McClung 2001b).

TABLE 18 *Avalanche runout summary statistics: mean values (source Smith and McClung 1997)*

Mean values	Canadian Rockies $n=127$	Coastal Alaska $n=52$	B.C. Coast Range $n=31$	Columbia Mtns* $n=46$
α	27.8	25.4	26.8	32.5
β	29.8	29.6	29.5	34.2
δ	5.5	5.2	5.5	34.2
H	869	765	903	538
L				8702
Δ_x	168	302	229	38
Δ_x / X_β	0.114	0.25	0.159	0.064

Note: The Columbia Mountains data describe high-frequency avalanche runout (i.e., less than ten-year events).

TABLE 19 *Avalanche runout summary statistics: extremes (source Smith and McClung 1997)*

Values	Canadian Rockies $n=127$	Coastal Alaska $n=52$	B.C. Coast Range $n=31$	Columbia Mtns $n=46$
α min	20.5	18.9	20.4	25.4
β min	23.0	23.0	22.8	27.0
δ min	21.5	0.0	5.0	25.0
H min	350	320	426	125
L max				2372
Δ_x max	542	790	1150	217
Δ_x / X_β max	0.40	0.66	0.56	0.32

Note: A negative delta angle indicates upslope avalanche runout (i.e., run up on the opposite valley wall).

McClung and Mears (1991) define a runout ratio (Δ_x / X_β), a dimensionless measure of extreme avalanche runout, for the prediction of zones affected by high-frequency avalanching as:

$$\frac{\Delta_x}{X_\beta} = \frac{\tan \beta - \tan \alpha}{\tan \alpha - \tan \delta}$$

Tables 18 and 19 shows how extreme runout summary statistics vary with the terrain properties found in different mountain ranges (Smith and McClung 1997; McClung 2001b).

TABLE 18 *Avalanche runout summary statistics: mean values (source: Smith and McClung 1997)*

Mean values	Canadian Rockies n=127	Coastal Alaska n=52	B.C. Coast Range n=31	Columbia Mtns* n=46
α	27.8	25.4	26.8	32.5
β	29.8	29.6	29.5	34.2
δ	5.5	5.2	5.5	34.2
H	869	765	903	538
L	–	–	–	8702
Δ_x	168	302	229	38
Δ_x / X_β	0.114	0.25	0.159	0.064

**Note: The Columbia Mountains data describe high-frequency avalanche runout (i.e., less than 100-year events).*

TABLE 19 *Avalanche runout summary statistics: extremes (source: Smith and McClung 1997)*

Values	Canadian Rockies n=127	Coastal Alaska n=52	B.C. Coast Range n=31	Columbia Mtns n=46
α min	20.5	18.9	20.4	25.4
β min	23.0	23.0	22.8	27.0
δ min	-21.5	0.0	-5.0	-25.0
H min	350	320	426	125
L max	–	–	–	2372
Δ_x max	542	790	1150	217
Δ_x / X_β max	0.40	0.66	0.56	0.32

Note: A negative delta angle indicates upslope avalanche runout (i.e., run-up on the opposite valley wall).

The prediction of maximum runout for large avalanches is difficult and cannot be done with definitive precision. A probability or risk-based estimate may be the most reasonable approach to the problem.

McClung (2000) has demonstrated that the prediction of extreme avalanche runout in both space and time, based on application of a Gumbel analysis to describe the spatial distribution and Poisson process to describe the temporal distribution, can be extended to model width in the runout zone.

Statistical Concepts

In some fields of earth science (e.g., flood hydrology of major river systems), there are sufficient high-quality data to characterize the frequency and magnitude of large events. Although more data exist on snow avalanches than on other, less frequent, mass movement phenomena (such as debris flows and landslides), observational data in British Columbia typically extend back only 25 years and may be available only for narrow corridors.

Some of the terms that are commonly used for land use planning with respect to floods are also used when describing avalanche frequency, magnitude, and runout distance. However, it is critical to recognize the limitations of the available avalanche occurrence data in comparison to hydrological databases.

When estimating the frequency of large avalanches at some critical point of interest (e.g., at a road or bridge), an extreme event can be regarded as a random variable with a given probability of occurrence. A probabilistic analysis is appropriate because the critical combination of weather variables (snowfall, wind, and temperature)—given the pre-existence of a weak layer in the snowpack—is highly unpredictable. A probabilistic approach is further justified because, in many interior British Columbia environments, avalanche magnitude cannot be correlated with frequency of major storms.

When applying probabilistic methods to snow avalanches, it is important to be clear as to whether the modeller is discussing runout distance or event magnitude. The following discussion is limited to runout distance.

The important probabilistic concepts used in discussion of runout distance are:

Annual Exceedance Probability (AEP).
The probability (P) that an avalanche runout (A) will exceed a given point of interest (a) in the avalanche path at least once in a year:

$$\text{AEP} = P(A > a)$$

Annual Non-Exceedance Probability (ANEP).

The probability that an avalanche will not reach the point of interest in the avalanche path in any given year:

$$\text{ANEP} = P(A < a)$$
$$= 1 - P(A > a)$$

Return Period (T) (also called the **recurrence interval** of an event).

The average length of time between consecutive events that reach the point of interest. Return period and AEP are inversely related:

$$T = 1/\text{AEP} \quad \text{or}$$
$$\text{AEP} = 1/T$$

The following examples consider a hypothetical avalanche that reaches a given point in its runout zone, on average, once in 30 years. If a structure such as a bridge is to be placed at that point, then an engineer might call that 30-year event the "design avalanche." Any event that overruns that given point (i.e., exceeds it) will damage or destroy the bridge.

The probability that an avalanche will run beyond the 30-year design point in any one year is:
$\text{AEP} = 1/30 = 0.033$

The probability that an avalanche will not run past the 30-year design point in any one year is:
$1 - \text{AEP} = 1 - 1/30 = 0.967$

Jargon in Risk Communication

The phrase "return period" is often used in civil and structural engineering, when a structure or protection system is designed to withstand an impact of a certain magnitude event. In that context, a 100-year "design avalanche" is assumed to have a certain size, speed, and impact pressure at the point where the structure is proposed.

The phrase "a 100-year return period avalanche" does not mean that an avalanche will occur only once in 100 years. A 1 in 100-year return period avalanche is better described as an avalanche with a 1 in 100 chance of occurring annually.

Here, the use of "return period" can lead to considerable confusion and should be avoided in other than highly technical discussion.

3.8 IMPACT PRESSURES

Impact pressure is a function of density (ρ) of the flowing speed, multiplied by the square of the speed (v), expressed as units of force per unit area on an object positioned perpendicular to the flow direction. The force is normally averaged through the time of the avalanche to give an average impact pressure.

Impact pressure (in kilopascals) = $\rho \times v^2$
where 1 kPa = 1000 N/m^2
Large, high-speed dry flowing avalanches are likely to exert the greatest impact pressures.

Studies from Rogers Pass, B.C. and elsewhere have shown that the maximum impact pressure occurs as the frontal pulse of an avalanche strikes an object perpendicular to the flow direction. Maxima occur within the first second or two of impact (McClung and Schaerer 1993, p. 112). In a dry flowing snow avalanche, peak pressure may be two to five times the average impact pressure. Large dry snow avalanches typically have impact pressures in excess of 100 kPa (≈10 t/m^2).

In recent field measurements in Switzerland, recorded impact pressures averaged around 80 kPa for the first 6 seconds during a large avalanche, with many peaks of 200–400 kPa and a few strong peaks of up to 1200 kPa (Figure 95; Dufour et al. 2000).

Keylock and Barbolini (2001) discuss vulnerability relationships for different-sized snow avalanches, as a function of runout distance. Table 22 gives typical relationships between impact pressures and potential damage.

TABLE 20 *Relation between impact pressures and potential damage (after McClung and Schaerer 1993)*

Impact pressure (kPa)	Potential damage
1	Break windows
5	Push in doors
30	Destroy wood frame structures
100	Uproot mature spruce trees
1000	Move reinforced concrete structures

Note: Impact pressures are often expressed as tonnes force per square metre rather than the SI unit of kilopascal (100 kPa is approximately equal to 10 t/m^2).

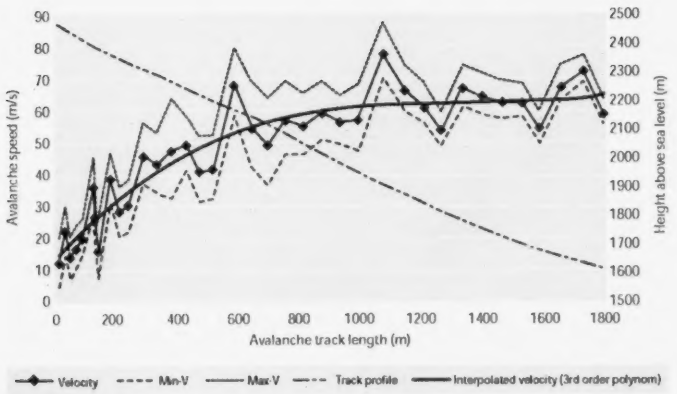


FIGURE 95a *Radar speed measurements of the frontal pulse of a large avalanche gave a maximum of 80 m/s (290 kph) (dashed lines indicate error ranges associated with the measurements). The path falls 900 m. (Dufour et al. 2000)*

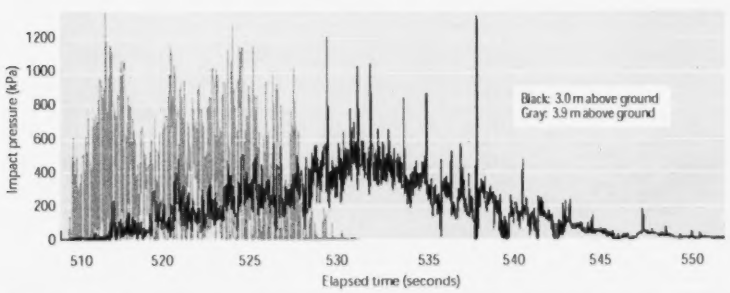


FIGURE 95b *Impact pressures measured at two heights on a tower located in the path shown above. At 3 m above the ground quasi-static pressures were around 500 kPa for 30 seconds, with distinct peaks of up to 1200 kPa. (Dufour et al. 2000)*

Mitigation 4

European countries have a long history of forest harvesting in snow avalanche-prone terrain but clearcut logging is no longer practised on steep mountain slopes. Because forest practices in British Columbia are markedly different from those in Europe, little guidance for cutblock design is available.

Current research indicates that many cutblocks exist on potential avalanche terrain in areas with a high snow supply. However, only a few cutblocks produce destructive avalanches between harvest and the time when canopy closure is sufficient to change the snowpack and its energy balance. Avalanche initiation is conditional on the occurrence of some critical combination of weather and snowpack in the vulnerable post-harvest period.

Engineering specifications for avalanche-inhibiting structures built in start zones in Europe and Japan require dense networks of snow-supporting fences to be constructed from heavy materials with very solid foundations (Figure 96). The implication is that retaining a low density of mature trees on a slope (e.g., a typical seed tree retention prescription of 50 stems/ha) is likely to have no effect in reducing avalanche frequency or magnitude.

FIGURE 96 *Typical engineered structures used in Europe to prevent avalanche initiation or arrest any small events that do occur.*

4.1 HARVEST DESIGN

Cutblock design should be considered in the context of the scale of topographic features that control snow accumulation and, hence, loading of any slope. Many effects occur at the micro- and local scale,

whereas severe weather occurs at the meso-scale (Table 21) (Weir and Auer 1995; Hageli and McClung 2000).

TABLE 21 *Scale effects on snow accumulation*

Scale	Distance	Example
Micro	1 m–10 m	Lee of ridge top or rock outcrop
Local	10 m–1 km	Gully or cutblock
Meso	1 km–50 km	Valley system
Regional	50 km–500 km	Entire mountain range
Macro	> 500 km	Synoptic weather system

Slope Length

Preliminary field surveys undertaken in British Columbia forests point to a relationship between length of slope in the cutblock and susceptibility of the downslope forest to avalanche damage, but research on avalanche penetration into standing forest is incomplete (D. McClung, University of British Columbia, pers. comm.). There is likely to be some threshold slope distance beyond which a given size of avalanche (i.e., Size 3 or larger) will develop sufficient speed to generate impact pressures capable of breaking mature timber. Slope lengths greater than 200 m are considered to pose moderate risk, while slope lengths greater than 400 m are considered to pose high risk, in combination with other factors (McClung and Stitzinger 2002).

Cutblock width (i.e., the distance parallel with the contour) is less critical than slope length, but does affect wind exposure. Wider blocks offer a greater length of fetch for wind to entrain new snow and redeposit it in areas lee to local-scale topographic features.

There is little documented research on the influence of alternative cutblock size and shape on avalanche occurrence. However, basic principles can be used to develop harvest systems to reduce risk factors. Foresters and avalanche assessors are encouraged to work together to devise suitable systems. Forest managers should balance the severity of avalanche risk against forestry constraints, such as age class, species and structure, forest health, and the availability and operating costs of suitable harvesting equipment. Alternatives to large clearcuts should be considered on steep slopes at higher elevations, because of the greater likelihood of avalanching due to the higher snow supply, and because of the slower growth rates that delay the establishment of new forest.

The benefits of small patch cuts and other alternative designs should be weighed against the range of costs associated with increased road density; apart from greater capital expense, environmental costs may arise from site degradation and soil losses and potentially an increased landslide frequency. It may be possible to offset these costs by using temporary roads and forwarding trails.

Recommendations are Interim

Any recommendations made here should be regarded as provisional. Little is proven about the effects of harvest design on avalanche initiation or avalanche penetration into standing forest. On-going research at the University of British Columbia is expected to shed light on some of these issues.

Strategies that reduce the avalanche risk should be considered early in the Forest Development Plan process, before road layout and cutblock design are determined. Opportunities to fine-tune the prescription for a previously laid-out cutblock are likely to be limited.

Lateral yarding with a motorized carriage offers the possibility of harvesting timber along the contour or in a chevron pattern on steep terrain while maintaining reduced downslope lengths in openings (Figure 97). Harvest costs are higher because of the extra equipment involved but the risk of producing destructive avalanches may be significantly reduced.

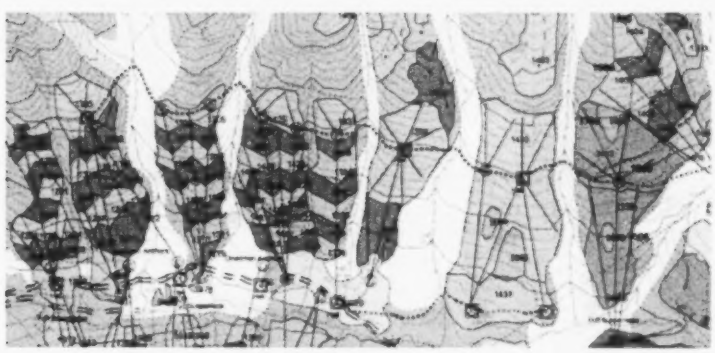


FIGURE 97 *The Total Chance Harvest Plan proposes alternative block designs for cable harvesting on slopes steeper than 60% in a high snowfall area. Avalanche assessments indicated that avalanches of greater than Size 3 would likely initiate once in 10 years if large clearcuts were created in the area. (Total Chance Harvesting Plan by G. Sime, RPF, Silvatech Consulting, for MoF Arrow Lakes Forest District and Pope and Talbot, Nakusp, B.C.)*

FIGURE 98 *The length of fetch for wind-transported snow is greatly reduced in small openings. Group selection harvesting (cutting of small patches) is less likely to produce areas prone to generating destructive avalanches, than is harvesting of large clearcuts.*

FIGURE 99 *Group selection using small cable or helicopter harvesting systems is appropriate in steep terrain in areas of high snow supply. Destructive snow avalanches (Size 3 or greater) are unlikely to occur in small openings.*

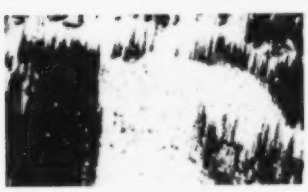


FIGURE 100 *Tree patches retained in steeper terrain alter the radiation balance over the snowpack, intercept snowfall, and alter local wind flow. High stumps increase the surface roughness and provide some mechanical reinforcement to the snowpack.*

This may affect the economics of harvesting lower-quality forest stands in steep terrain. Note that maintaining a short slope distance when contour-logging in steep blocks may bring the added benefit of reducing visual impacts.

Small patch cuts or single tree selection where timber is extracted by helicopter is another method of reducing the total opening size and reducing the potential for creating large avalanche start zones (Figures 98 and 99). A 1-ha opening (50 m downslope × 200 m parallel with the contour) may represent a reasonable dimension.

Retention of timber reserves at potential avalanche initiation points within steep cutblocks should be considered during block design. Such reserves may have ecological value, as wildlife tree patches, for example (Figure 100). Existing avalanche paths can be extended laterally and longitudinally if adjacent tree cover is removed. Frequent disturbance by even small avalanches can make it impossible to re-establish a free-growing new plantation.

Areas surrounding outcropping rock, steep cliff bands, old landslide head scarps, or concave depressions should be considered for timber reserves. In terrain over 30° (60%), some of these same geomorphological features may pose constraints on harvesting because of other geotechnical concerns or potentially elevated risk of mass failure, especially if the surface topography suggests that drainage is convergent. These issues should be identified during a Terrain Stability Field Assessment, and mitigative strategies detailed in the silvicultural prescription (Figures 101–103). Retention of timber in such areas may serve multiple objectives.

In Figure 97, natural avalanche paths (mapped in white) that initiate in alpine zones dissect the forest and run out into a fish-bearing creek (designated S2). The Total Chance Harvesting Plan calls for wildlife buffers to be retained around avalanche tracks and runout zones, in accordance with the Kootenay-Boundary Land Use Plan's provision for grizzly bear habitat (KBLUP Resource Management Zone Objective 5). A wildlife connectivity corridor, set out on slopes of less than 80%, has been proposed to cross the creek at the western boundary of the area.

FIGURE 101 *Silviculture prescription specifies retention of high stumps (0.8–1.2 m) at a density of 100 stems per hectare and retention of trees with dbh of less than 17.5 cm in areas susceptible to avalanche initiation. (P. Gribbon RPF, Downie Street Sawmills)*

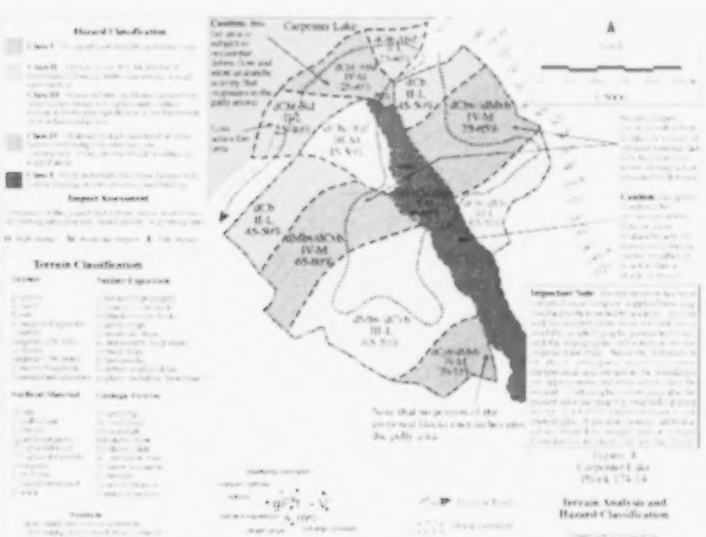


FIGURE 102 *Polygon-based 1:5000 scale mapping produced during a Terrain Stability Field Assessment. A snow avalanche path was identified running from the gully within a proposed block to the fan below. (Baumann Engineering)*

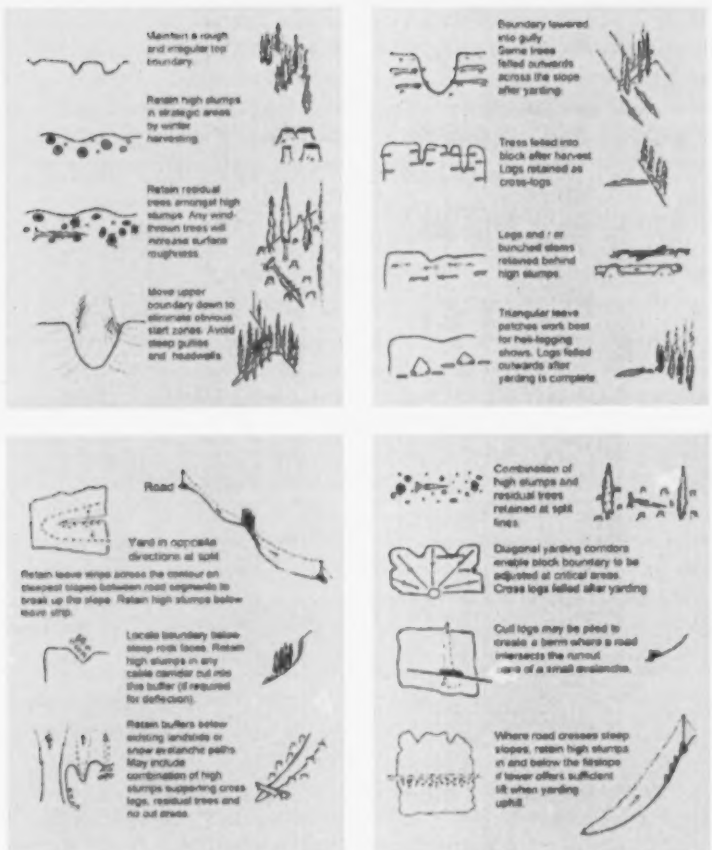

Maintain a rough and irregular top boundary.
Retain high stumps in strategic areas by winter harvesting.
Retain residual trees amongst high stumps. Any wind-thrown trees will increase surface roughness.
Move upper boundary down to eliminate obvious start zones. Avoid steep gullies and headwalls.
Boundary lowered into gully. Some trees felled outwards across the slope after yarding.
Trees felled into block after harvest. Logs retained as cross-logs.
Logs and / or bunched stems retained behind high stumps.
Triangular leave patches work best for heli-logging shows. Logs felled outwards after yarding is complete.
Road
Yard in opposite directions at split
Retain leave strips across the contour on steepest slopes between road segments to break up the slope. Retain high stumps below leave strip.
Locate boundary below steep rock faces. Retain high stumps in any cable corridor cut into the buffer (if required for deflection).
Retain buffers below existing windfalls or snow avalanche paths. May include combination of high stumps supporting cross logs, residual trees and no cut areas.
Combination of high stumps and residual trees retained at split lines.
Diagonal yarding corridors enable block boundary to be adjusted at critical areas. Cross logs felled after yarding.
Cull logs may be piled to create a berm where a road intersects the runout zone of a small avalanche.
Where road crosses steep slopes, retain high stumps on and below the fillslope if lower offers sufficient lift when yarding uphill.

FIGURE 103 *Block layout strategies to reduce avalanche susceptibility. (Designs developed by A. Freeland 1991)*

Chevron-shaped patches are proposed for harvest on the first and third logging pass, about 40 years apart, to allow for regeneration in adjacent areas. Harvest systems will employ a motorized carriage with downhill yarding. The typical vertical fall in each patch is 60 m and slope distance is 100 m. Narrow yarding corridors (purple lines) will not be replanted until after the third pass through the area.

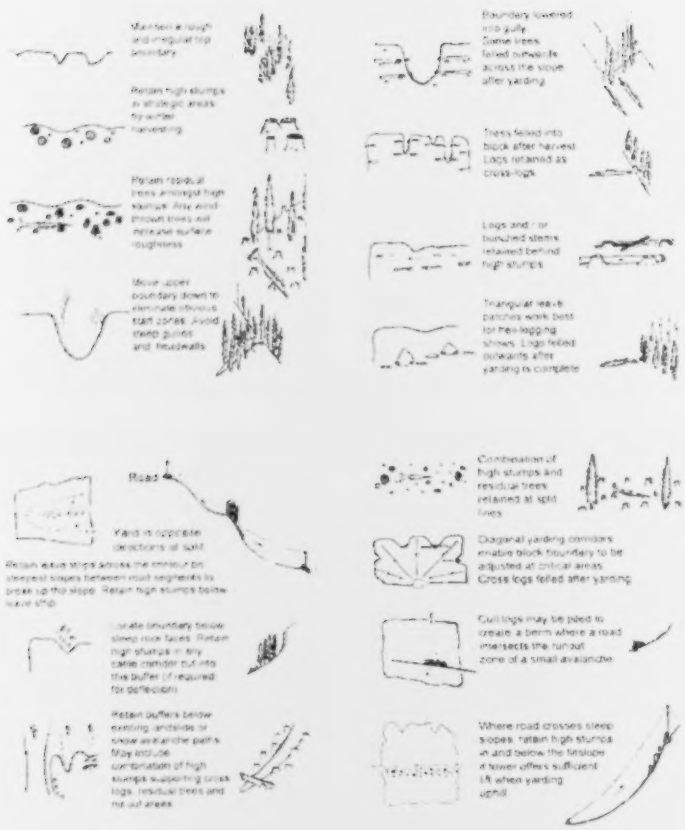

Boundary lowered into gully. Some trees felled outwards across the slope after yarding
Trees felled into block after harvest. Logs retained as cross-logs
Logs and / or bunched stems retained behind high stumps
Triangular leave patches work best for helilogging shows. Logs felled outwards after yarding is complete
Road
Yard is opposite directions of spiral
Combination of high stumps and residual trees retained at split lines
Diagonal yarding corridors enable block boundary to be adjusted at critical areas. Cross logs felled after yarding
Cut logs may be piled to create a berm where a road intersects the runout zone of a small avalanche
Where road crosses steep slopes, retain high stumps on and below the fillslope. A lower offers sufficient lift when yarding uphill

FIGURE 103 *Block layout strategies to reduce avalanche susceptibility. (Designs developed by A. Freeland 1991)*

Chevron-shaped patches are proposed for harvest on the first and third logging pass, about 40 years apart, to allow for regeneration in adjacent areas. Harvest systems will employ a motorized carriage with downhill yarding. The typical vertical fall in each patch is 60 m and slope distance is 100 m. Narrow yarding corridors (purple lines) will not be replanted until after the third pass through the area.

4.2 SILVICULTURAL STRATEGIES

Some of the strategies suggested below are considered by experienced foresters to reduce the avalanche susceptibility of harvested areas. Other strategies seem intuitively correct, but must be regarded as interim and unproven. Most of these strategies will be less effective in areas of high snow supply.

Principles of positive adaptive forest management indicate that if two or more silvicultural strategies are applied in similar terrain to mitigate avalanche damage, then annual avalanche monitoring may improve our understanding of strategies that reduce avalanche susceptibility (Taylor et al. 1997).

Increasing Surface Roughness

Start zones with rough surfaces appear to display a lower frequency of snow avalanching than those with smooth surfaces (e.g., grass, smooth rock slabs, or fine talus slopes). In forestry situations, surface roughness is markedly reduced where a broadcast burn is prescribed or where stumps are cut close to the ground to improve deflection for cable logging.

Early winter avalanche thresholds (the depth of snow required to predispose a steep slope to avalanching) will depend on surface roughness.

Retention of High Stumps

Retention of tree stumps appears to reduce or inhibit the release of full-depth avalanches. Some logging companies in British Columbia schedule harvesting from mid- to late winter to maximize the height of retained stumps. The risk trade-off is that workers may be exposed to periods of avalanche danger that do not exist in other seasons.

A high-stump prescription may be appropriate in old cedar stands if the lower boles exhibit high levels of decay and are of no merchantable value. Stumps are likely to last longer in Interior Cedar–Hemlock (ICH) forests compared to Engelmann Spruce–Subalpine Fir (ESSF) forest types.

If high stumps are to be prescribed, then the avalanche assessor and the forester should communicate or, better yet, visit the field together to ensure this is feasible. One company reports that a workable prescription is to cut trees at a height of 30 cm above the snowpack during winter harvesting. Retention of high stumps may also reduce the frequency of hard slab avalanches in low to average snow years, but prompt, successful restocking is the key to minimizing avalanche activity.

Retention of high stumps can make cable logging difficult or impractical, especially where only partial suspension can be achieved on lines with poor deflection. Several companies report that high-stump prescriptions are often too difficult to work with and pose a danger to workers. High stumps also reduce the potential value of a cutblock for winter recreation.

Avalanche-inhibiting structures built in the start zone are generally designed to be as high as the maximum expected snowpack. If such structures become buried and a weak layer develops above them, they will have no effect in preventing avalanches involving new snow layers in heavy snowfall winters. The implication is that the strategy of leaving a dense network of high stumps on a clearcut does not guarantee protection against avalanches in all conditions.

Given that avalanches preferentially release below steep bands of outcropping rock or rock pinnacles, a retention of high stumps may reduce the susceptibility of such an area to avalanching. A high-stump prescription may be appropriate in some harvest scenarios or in selected areas within a clearcut but is not a universal remedy.

Stethem et al. (1996) cited a Japanese study of an area with a 3- to 5-m snowpack. It was found that half the stumps in a block had rotted and overturned 9 years after logging. Full-depth avalanches occurred after stump densities decreased to 100 stumps per hectare (Saeki et al. 1981).

High stumps endure greater turning moments under snow creep and so are more likely to be torn out once primary rootlets decay. High stumps generally do not provide long-term protection against avalanches. For tree species other than cedar, significant root deterioration usually occurs at 5–15 years after harvest (Sidle 1991; Watson et al. 1999). Prompt successful reforestation is key to reducing avalanche susceptibility. High stumps should not be relied on in a high-risk (high-consequence) situation (e.g., where there is a highway or a dwelling downslope of the proposed cutblock).

Planting on the downhill side of stumps reduces the effect of snow creep on seedlings, which may otherwise produce J-shaped trunks.

Biological aspects should also be considered in the analysis. Woody debris offers good habitat and cover for some species. However, the increased likelihood and consequences (risk) of harbouring insect populations (e.g., spruce bark beetle) in decaying stumps may offset some benefits.

Cross Log Retention

Retaining high stumps, in conjunction with leaving logs across the slope, will impede snow glide and in that way assist reforestation (Figure 104). One forest operator reported trials using a helicopter grapple to position cross logs. Others emphasized the impracticality and difficulty, if not the threat to the safety of workers involved, in trying to arrange cross logs with cable harvest systems.

In western Austria, a combination of high stumps and cross log retention is recommended to reduce avalanche susceptibility following harvest (Heumader 1999).

FIGURE 104 *Logs retained by high stumps used to inhibit snow creep and glide in a gully.*

Slash Loading

Forest companies operating near Revelstoke, an area of high snow supply, report that full depth avalanches do not appear to occur in blocks with high slash loading. In the Nagle Creek example (described in Section 6.6) only one of three adjacent cutblocks avalanched. The affected block had the least amount of retained slash and least rough surface (Figure 105).

FIGURE 105 *Avalanche initiated at a convex change in slope where stump height was reduced to improve deflection for cable yarding. Fracture depth was 0.8–1.2 m, while stumps were locally 0.3 m.*

Retention of Understory

Retention of understory and non-merchantable trees (less than 17.5 cm dbh) and advanced regeneration assists in maximizing the surface roughness. Combining these strategies may provide benefit beyond the time when the majority of tree stumps and roots have rotted.

Avoidance of Broadcast Burning

A general consensus is that broadcast burning should be avoided and that the non-merchantable understory should be retained to increase the surface roughness in potential avalanche start zones.

Modification of Local-scale Climate

Partial cut systems (e.g., variable retention) may alter the local wind fields and the energy balance over the snowpack. Snow falling from retained trees may disturb layering and reduce surface hoar build-up sufficiently to reduce the susceptibility for avalanching. This strategy may also assist in attaining objectives for protection of wildlife habitat (see Section 2.8, "Ecological Significance").

In areas with low to moderate snow supply, strategically placed tree patches and reserves, and a reduction of cutblock size, may reduce the amount of wind-transported snow available to load start zones.

Retention of Timbered Margins Adjacent to Avalanche Runout

Trees beside confined avalanche paths limit the spread of small- to medium-sized avalanches, particularly in lower-gradient parts of the runout zone. Conservative margins should be retained on both sides of gullies where avalanches run, to prevent the lateral and lineal extension of existing avalanche paths (Figure 106).

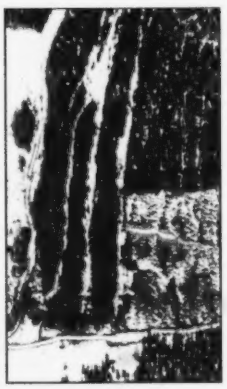


FIGURE 106
Cutblock boundary set too close to gullies where avalanches run. Avalanches are likely to break out into the openings, reducing the success of forest restocking.

Species Vulnerability

With regard to the vulnerability of the forest downslope of clearcuts with a high avalanche potential, numerous variables must be considered, including tree species, dbh, and age class. Natural selection has equipped certain ecosystems to survive snow creep and endure avalanche impact. Alder is perhaps the most resilient species, and so it is often found growing in avalanche paths. Cedar and hemlock are considered to be moderately well adapted and have higher tolerance thresholds, while spruce and balsam are intolerant of avalanche impact.

The Swiss have conducted research on snow creep, snow glide, and avalanche forces on trees and have produced guidelines on the density of trees necessary to resist the forces as a function of the slope incline, ground roughness, and snow conditions (Salm 1978). This finding is unproven in British Columbia.

4.3 EFFECTS OF HARVESTING ON HELISKI, SNOWCAT, AND WILDERNESS SKIING OPERATIONS

Heliski, snowcat, and wilderness skiing, and other backcountry winter operations, are licensed and authorized to use forested land in British Columbia. Clearcut logging can compromise avalanche safety in such operations.

In eastern British Columbia, where the majority of heliski operations are located, experience has shown there is an abnormally high incidence of

surface hoar formation in clearcuts (compared with many other mountain ranges). This has the effect of excluding significant amounts of harvested terrain from being usable for skiing in many winters, because buried surface hoar increases the risk of avalanching. Based on the Canadian system for avalanche sizes, a practical upper limit to acceptability for skiing parties is an avalanche of Size 1.5 (Table 4). Thus, when slope angles exceed 25° (50%), clearcut logging above or in established ski runs and other skiable terrain will virtually always create or increase avalanche potential and influence safety and operational issues for heliski and snowcat-skiing operators and the public. Ideally, harvest plans should address input from all licensed users of forested land, include broad considerations of the increased risk to safety, and incorporate an analysis of benefits versus all costs and externalities.

Heliski operations often confine their skiing to below the treeline when the avalanche danger is high in alpine areas or when poor flying conditions occur above the treeline. Heliski operators take advantage of frequent skier traffic to compact the snow and disturb weak layers (thus decreasing the snowpack instability), but this is not always possible.

Canadian Mountain Holidays Heliskiing employs an experienced forestry technician to plan cutblocks that offer skiing potential and provide harvesting opportunities for the forest industry. Narrow, vertically oriented cutblocks provide an important example of co-operation between the forest and tourism industries and the Ministry of Forests (Figure 107).

4.4 STREAM CROSSING LOCATION AND ROAD LAYOUT

The following principles should be considered when designing stream crossings and laying out roads that will be used in winter and in avalanche-prone terrain.

- Bridges in avalanche paths may be extremely vulnerable (Figures 108–109). It is difficult to provide sufficient clearance for an avalanche mass to travel under a bridge. Innovative design is required for a bridge that is to withstand likely impact pressures (Figure 110). Rock fords may provide more suitable crossings (Figure 111). Note that culverts may be required below the ford to ensure fish passage (refer to the *Stream Crossing Guidebook for Fish Streams* [B.C. Ministry of Forests 2002]).

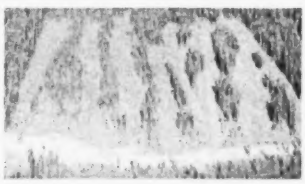


FIGURE 107 *These narrow, vertically oriented cutblocks set out for heliskiing in the Bugaboos are designed to minimize avalanche susceptibility. Soft edges are created to minimize visual impacts in cutblocks used by an international heliski clientele. Forest management and harvesting can be integrated to maximize recreational and harvesting opportunities while minimizing avalanche potential.*

a)

b)

FIGURE 108 *A poor bridge location directly in line with the runout of a large snow avalanche path (bottom centre of photo a). The Bull River bridge had been in place for 30 years before being impacted by a large avalanche.*

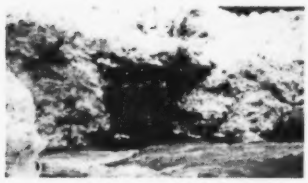


FIGURE 109 *Bridge span destroyed by a large snow avalanche.*

- The flow direction of wet snow avalanches can be unpredictable. Road designers should roll the grade down into a crossing to reduce the possibility of any avalanche mass leaving the channel and flowing down the road.
- Large avalanches seldom run the full length of long concave profile paths. A road that crosses low in the runout zone will be affected less often than a road that crosses upslope in the track. Note that this may conflict with wildlife habitat protection objectives (see Habitat Protection Guidelines, p. 43). Roads in or immediately below avalanche start zones or high in the track (or roads that cross through steep clearcuts in areas of high snow supply) will present a high hazard in many winters (Figure 112).
- The probability of a moving vehicle being struck by an avalanche is very low. However, any vehicle stopped or stuck in an avalanche path during a severe storm or at times of high snow instability may be at significant risk.

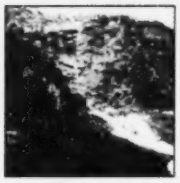
Even a small amount of avalanche debris on the road will stop a truck. A high-hazard situation exists when a number of avalanche paths intersect a road at close intervals, especially if there is no opportunity for a loaded logging truck to turn around between paths.

Turnouts and turn-around points, chain-up areas, rescue caches, landings, fuel caches, and similar sites and equipment should be located in designated safe stopping areas. Where forest roads cross avalanche paths, the general grade should be reduced to prevent the possibility of a laden truck becoming stuck at times of heavy snowfall (when the avalanche danger is often rising).

Logging around a switchback or setting out a switchback within a steep cutblock increases the exposure and hence the risk (Figures 113 and 114). Road designers should consider the road location relative to cutblock boundaries and also the increased avalanche susceptibility from fillslope

over-steepening. When assessing the potential for snow avalanche initiation from a road user perspective, it is safer to locate a road across the top of an existing cutblock, or locate new cutblocks below roads (Figure 113).

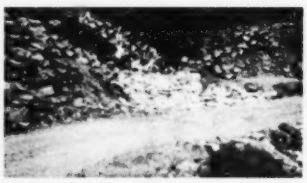
Excavation of a road through or at the base of a steep continuous slope within a cutblock may remove the area where a snow slab might otherwise be supported in compression. Locally over-steepened fillslopes seem to create favoured points for avalanche initiation in steep terrain in areas of high snow supply (Figure 115) (see the Nagle Creek case study, Section 6.6).



a) A low-profile slab girder bridge designed at a site frequently overrun by snow avalanches.

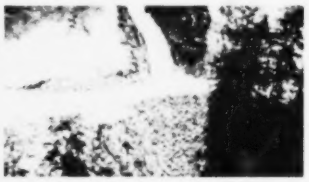
b) The deck is movable to allow for periodic removal and cleaning. The clearance below the deck is approximately 0.6 m.

c) The bridge consists of concrete slab girders supported on lock-block abutments.

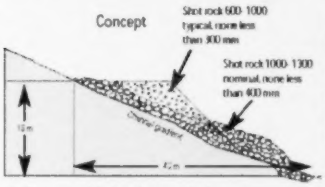


d) The channel was graded into the structure by placing boulders to provide a gradual transition over the structure for the flowing core of the avalanche mass.

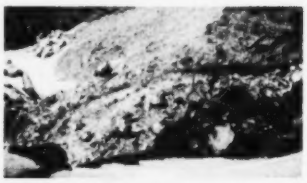
FIGURE 110 *Alternative bridge design for a high-frequency avalanche path containing a stream that has permanent flow.*



a) & b) Road crossing constructed by careful placement of very large angular rock.



c) Conceptual design shows rock placement schedule.



d) Avalanche debris over site after completion. Note person (circled) for scale.

FIGURE 111 *Rock ford used to cross the track of a large avalanche path.*

FIGURE 112 *Forest roads that cross high in an avalanche track will be affected more often. A valley floor road location generally offers less risk, but avalanche deposits may be deeper than upslope. However, roads that cross through runout zones may degrade grizzly bear habitat.*

FIGURE 113 *Use of this switchback section of road in winter prolongs exposure to avalanches. Harvesting above forest roads increases the avalanche risk faced by winter road users.*

Small bladed trails and roads may break up smooth slopes, increasing surface roughness and reducing susceptibility to glide avalanching. However, this must not be adopted as a universal prescription because bladed trails can intercept and redirect shallow groundwater and lead to misdirected drainage and landslides.

Where a number of avalanche paths intersect a mainline road in high-hazard areas, a simple cache of rescue equipment should be stored at a suitable location (e.g., a primary intersection) or on either side of major avalanche paths.

On high-traffic mainline roads crossing avalanche paths, "No Stopping" signs should be erected.

"Avalanche Area" signs should be posted around individual paths rather than one sign being posted at each end of several kilometres of road where perhaps six 40 m wide paths may intersect the road. This heightens awareness and is good risk communication: signed areas are clearly identifiable as avalanche areas. In the event of an accident, the rescue party can also use the signs as an indicator of how close they can approach and still be safe (the avalanche may have occurred at night, or whiteout conditions may exist at the time of the incident). Managers cannot assume that the rescue team will be familiar with the area. Signage should be taken down in summer to maximize its impact

during the winter avalanche season. Good signage assists in the application of Safe Work Procedures (Appendix 2) (L. Redfern, RPF, Crestbrook Forest Industries, pers. comm.).

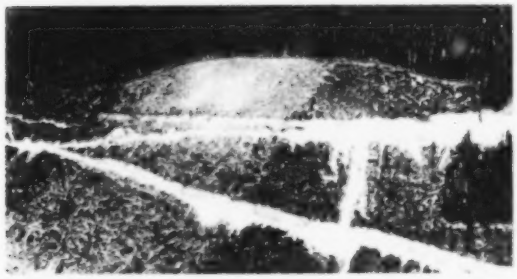


FIGURE 114 *Avalanche path on the public road to Shames ski area, Terrace. The fillslope below the upper road section (right of centre) appears to have failed, creating a small convex bowl where avalanches may initiate.*

FIGURE 115 *Oversteepened road fillslopes that dissect large clearcuts in steep terrain are common points for avalanche initiation, especially in areas of high snow supply such as La Forme Creek in the Selkirk Mountains north of Revelstoke. Road deactivation measures that include the pull back of fill material may reduce, but will not eliminate, the long-term avalanche risk within clearcuts.*

Managing avalanche risks in winter 5

5.1 FIELD OBSERVATIONS AND RECORDING SYSTEMS

An observation and recording system needs to be in place if accurate avalanche predictions are to be made or if explosives-based control work is to be cost-effective. The Canadian *Observation Guidelines and Recording Standards for Weather, Snowpack, and Avalanches* (CAA 1995) stress that observations should be made in a consistent manner. Observations are best if collected on a regular schedule, while the breadth and depth of the system should reflect the severity of the avalanche problem in the area. The following model, which proposes three classes of data used in avalanche prediction, is useful in prioritizing the observation effort (McClung and Schaerer 1993, pp. 128–162) (Figure 116).

Class I data are stability factors and are considered to be the most relevant for assessing avalanche danger. The data are obtained at the snow surface and describe the relationship between downslope load and weak layers. They are essentially "bull's eye" indicators (LaChapelle 1980; Fredston and Fesler 1994).

Class II data are obtained within the snowpack and describe snowpack weaknesses and loads on weak layers. Skilled observers are required to obtain these data, which are often non-numeric and therefore recorded as symbols. Class II are data not readily amenable to quantitative analysis and may be subject to considerable spatial variability (McClung and Schaerer 1993, p. 166).

Class III data are essentially meteorological parameters obtained above the snow surface. They are point data and, as such, may not correctly describe the meso-scale spatial variability found in a mountain environment (Weir and Auer 1995). Class III data are easiest to obtain but are often less relevant than Class I or II data (McClung and Schaerer 1993, p. 162).

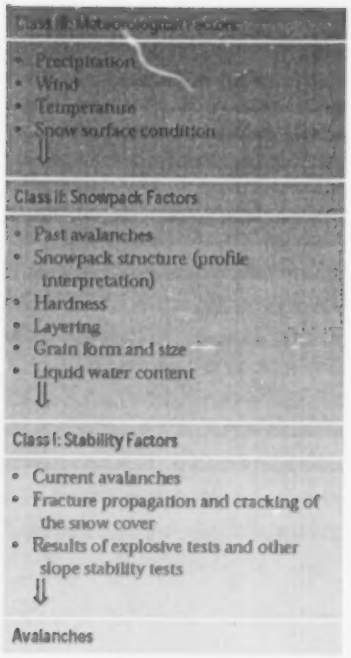


FIGURE 116 *Causal chain considered in avalanche prediction. The lower the class number, the more certain the interpretation and the more direct the evidence. (McClung and Schaerer 1993, p. 125)*

Given that Class I data are of the greatest value in predicting avalanches, priority should be given to collecting this information. Thus, most operations should aim to keep daily records of snow avalanche activity (and, equally important, records of non-activity). Field staff should be on watch for signs of snow instability, such as fracturing or cracking at the snow surface.

The frequency of snowpack observations (Class II data) will depend on the risk in the area. In low-risk areas, it may be necessary to routinely collect these data. The underlying implication is that weather observations (Class III data) should not be the only form of data collected.

5.2 CLASS I DATA: AVALANCHE OBSERVATIONS

All significant avalanches and other Class I data should be recorded in a field notebook (Figure 117). Noting the non-occurrence of avalanches is equally important. Important points are:

- Information about avalanche occurrences and non-occurrences is used in association with other observations in evaluating snow stability.
- Observations identify areas where avalanches have released earlier in the winter, and thus snow stability may vary between these sites and undisturbed slopes.
- Avalanche observation data are essential when protective works and facilities are planned, the effectiveness of control measures is assessed, and forecasting models are developed by correlating past weather and snow conditions with avalanche activity (CAA 1995).

Each month, a time-series plot of avalanche observations should be made on a large sheet of graph paper along with weather observations. These

Class III: Meteorological Factors

- Precipitation
- Wind
- Temperature
- Snow surface condition

⇩

Class II: Snowpack Factors

- Past avalanches
- Snowpack structure (profile interpretation)
- Hardness
- Layering
- Grain form and size
- Liquid water content

⇩

Class I: Stability Factors

- Current avalanches
- Fracture propagation and cracking of the snow cover
- Results of explosive tests and other slope stability tests

⇩

Avalanches

graphs will become the basis of an operation's avalanche evaluation program. The graphs will provide a ready reference if it becomes necessary to call in a specialist technician to assist with avalanche risk management. Time-series graphs encapsulate important knowledge that might otherwise be lost through staff turnover. Graphs also provide a clear audit trail and allow managers to judge the effectiveness of an avalanche control operation.

Avalanche Observations							Observer. *B. A.*					
Location *TFL 54, from 1100 Road*							Starting zone	Termi-nus	Forest damage	Road buried average		
Date	Time	Path	Type S / L	Aspt	Size	Trig	Elevation m		Ha	Long m	Depth m	Comments
010209	~	*Moose*	*S*	*NE*	*2.0*	*N*	*1700*	*MP*	*0.5*	*0*		
010209	*1500*	*km 18*		*N*	*3.0*	*N*	*1600*	*TR*	*0*	*50*	*4*	
010210	*1500*	*Bear 2*	*S*	*E*	*3.5*	*N*	*1850*	*BP*	*1.5*	*0*		*Broke old firs*
												Deposit 10 m
												deep in creek
010211	*1110*	*Dans*	*L*	*S*	*2.5*	*Xh*	*1800*	*TR*	*0*	*0*		*Heli bombing*
010211	*1115*	*9.2km*			*0*	*Xh*	*1600*					*No results*

FIGURE 117 *Sample page from field notebook of basic avalanche observations. (After CAA 1995)*

5.3 CLASS II DATA: SNOWPACK

Mountain snowpacks are known to exhibit a high degree of spatial and temporal variability. Site selection is important when undertaking *in situ* field tests, collectively termed a "snow profile study" (Figure 118). Site selection will determine the relevance and applicability of the data to the objective of assessing snow stability.

When a snow avalanche technician excavates a snow pit, the layer boundaries are identified and the form and size of snow grains within each layer are classified according to the 1990 International Commission on Snow and Ice classification system (Colbeck et al. 1990; CAA 1995).

The hardness and density of each layer are identified (these parameters can be correlated with snow strength for some grain forms). Temperature is measured at intervals up through the pack and the data used to calculate the gradient across each layer. If a layer is found to be at 0°C, then a simple measure of liquid water content is obtained.

FIGURE 118 *Snow profile studies conducted at fracture lines are used to identify failure layers.*

Once the individual layers have been described, the interface between layers and the properties of very thin layers are described. One or more stability tests will then be used to locate the weak layers in the snowpack (Figure 119). Consideration is given to the load on the weakest layer, as well as to the strength, hardness, and temperature of the layers above the weak layer.

FIGURE 119 *Shovel shear test is used to locate but not rate a weak layer or interface.*

A snow stability field test should aim for the following (Schaerer 1991):

- It should stress the weak layer in shear, not bending or compressing.
- The force applied must stress the snow to failure.
- The area under stress should be as large as possible.
- The test should be suitable for application both on a sloping and a level snow cover.
- Preparation of the test site and the repeated observations should require not more than 30 minutes.
- Any equipment used must be simple and portable.
- The test should give unbiased, quantitative, and objective information.

The Rutschblock test comes closest to meeting these criteria (Figure 120) (see Jamieson 1997, p. 17).

FIGURE 120 *The Rutschblock test requires a slope of 25° (47%) or more. An isolated block is progressively loaded until failure.*

FIGURE 121 *Snowpack observations conducted at safe sites at the elevation of avalanche start zones give relevant information for use in snow stability assessments.*

Experienced avalanche technicians (i.e., CAA Level 2 qualified) are trained to integrate snow profile data with other observations to make an assessment of snowpack stability for any given elevation and aspect (Figure 121). A standard snow stability rating system is presented in Appendix 6 (CAA 1995).

Skilled observers aim to answer the following critical questions when making snowpack observations to assess snow stability:

- Do weak layers or weak bonds exist in the snowpack?
- What is the strength of the weakest layers and bonds?
- What is the depth of the weakness below the surface and what is the snow load on the weakness?
- How strong are the snow layers above the weakness? (Does a slab exist?)
- How are the layers and weaknesses distributed across the terrain?

(McClung and Schaerer 1993, p. 141).

TABLE 22 *Basic snow grain classification (After Colbeck et al. 1990)*

Symbol	Basic classification	Code
+	Precipitation particles (new snow)	PP
/	Decomposing and fragmented particles	DF
•	Rounded grains (monocrystalline)	RG
□	Solid-faceted crystals	FC
^	Cup-shaped crystals (depth hoar)	DH
O	Wet grains	WG
V	Feathery crystals (surface hoar)	SH
▬	Ice masses	IM
⋈	Surface deposits and crusts	CR

TABLE 23 *Snowpack hardness test*

Symbol	Hand test	Term	Graphic
F	Fist in glove	Very low	
4F	Four fingers in glove	Low	/
1F	One finger in glove	Medium	X
P	Blunt end of pencil	High	//
K	Knife blade	Very high	⋇
I	Too hard to insert knife	Ice	▬

An experienced snow avalanche technician (holding a CAA Level 2 qualification) should be consulted to develop a suitable field observation program that meets the needs and circumstances of the forest operation.

Standard symbols are used to represent snow grain forms observed in each layer during snow profile analysis (Tables 22 and 23). Layer hardness is measured along with liquid water content.

Snowpack observations from field work should be plotted on a standard snow profile form (Figure 122). A template is available in the Canadian *Observation Guidelines and Recording Standards for Weather, Snowpack, and Avalanches* (CAA 1995). A PC (Windows personal computer) software application (Figure 123) is available to assist with this task and brings the added benefit of making the data available for other applications.

Snow Profile: Organisation *FPS.*						Observer: *P.M., A. LeB.*	Type: *Full*	
Date *20010228*			Time *1420*			Sky ⊕	Wind *Mod, SE*	
Location *Blk 83*			Elevation-*1810m*			Precip S *-1*	Air Temp *-2.0*	
Aspect *W*			Incline *10*			Foot Pen *32* cm	Surface *-2.5*	
H (cm)	R	F	E (mm)	θ	ρ (kg/m^3)	Comments / shear tests	H (cm)	T (°C)
138		+ r	*1*				*128*	*-0.5*
	F	*	*1*	*dry*	*80*		*120*	*0*
130							*110*	*0*
	F	/	*0.5*	*moist*	*160*		*100*	*-1.0*
112						*Rb 3 stellars at 112 cm*	*90*	*-2.0*
	4F	/ •	*0.3-0.5*	*dry*	*220*		*80*	*-4.0*
80							*70*	*-5.5*
	F	v	*4*		*~*		*60*	*-5.0*
78						*Shovel Easy at 78 cm*	*50*	*-4.0*
	1F	♦ •	*0.5*		*260*		*40*	*-3.0*
45							*30*	*-2.5*
	I	■			*~*	*ice layer*	*20*	*-2.0*
44							*10*	*-1.0*
	K	✕	*1-2*		*~*	*crust*	*0*	*0*
35								
	P	•	*1*		*330*			
18								
	1F	^	*3-5*	*Dry*	*290*	*partially rounded*		
0								

Abbreviations used (in columns from left to right) are:
H–Height of snow layer boundary (cm)
R–Resistance to penetration (hardness)
F–Grain form (Colbeck et al. 1990)
T–Temperature (°C) at height H
E–Grain size (b axis in mm)
θ–Liquid water content (squeeze test)
ρ–Density (kg/m^3)

FIGURE 122 *Standard field notebook set out for a full snow profile observation. (CAA 1995)*

Snow Profile Interpretation

A high level of experiential skill is required to interpret snow profile data and extract the Class II information used in avalanche prediction. This skill is developed through field experience and mentoring. Fracture line investigations offer important learning opportunities.

The B.C. Ministry of Transportation's Snow Avalanche Program has developed a knowledge-based expert system that runs on a PC for snow profile interpretation (Joseph 1994). The application, named "Snow Profile Assistant," encapsulates the knowledge of some of the most senior avalanche forecasters in the province and elsewhere. The system identifies the layers most likely to fail and rates the probability of failure at that layer (Figure 124). When appropriate, the system describes scenarios likely

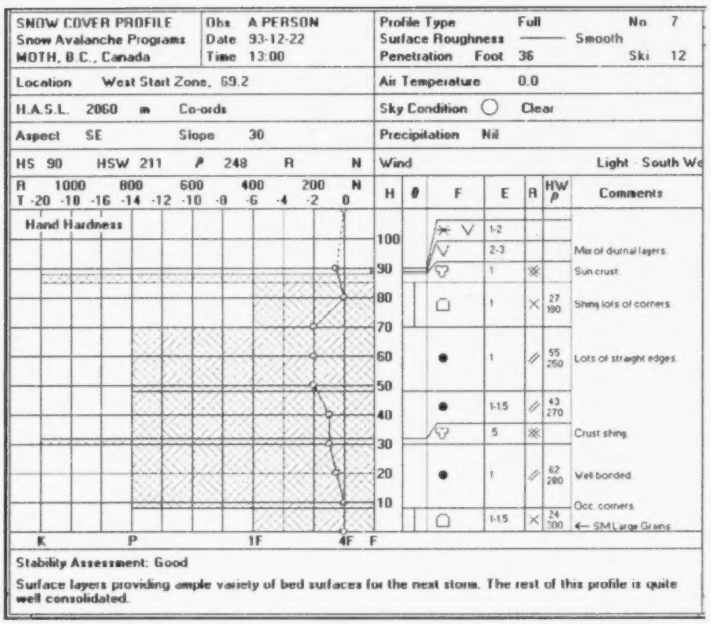


FIGURE 123 *Plot of a snow profile produced by PC application:*

- *Average snow density (ρ) and equivalent water content of each layer (HW) and whole pack (HSW) are calculated automatically.*
- *Hardness (H) is plotted as a horizontal bar graph on the left side of the profile.*
- *Snow temperature is plotted as a line.*
- *An assessment of snow stability should be given at the bottom of the page.*

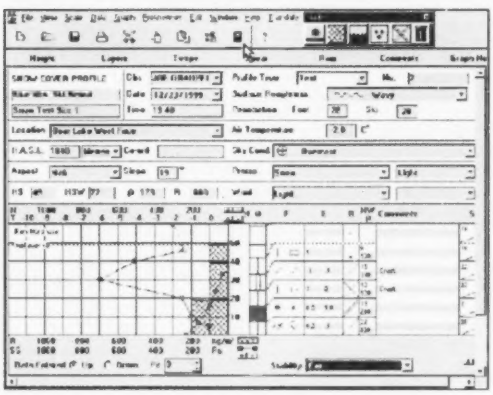


FIGURE 124 *Screen from a knowledge-based expert system designed to assist with snow profile interpretation. (Example shows "Snowpro" software used to interface to the expert system.)*

to lead to a failure (such as increased load or a rise in temperature). The system is ideally suited for use in a small operation where only one individual may have training in snow profile observation, interpretation, and avalanche forecasting (i.e., someone with CAA Level 2 training). Sole practitioners often benefit by having a second opinion when they are making critical judgements.

Numerical Avalanche Forecasting

Knowledge-based computer applications hold great potential for avalanche forecasting (McClung and Schaerer 1993, pp. 164–166). Bayesian statistics offer a solution to the problem of meshing the expertise of the human forecaster with the data processing capabilities of a computer (Press 1989; Weir and McClung 1994).

Considerable research was undertaken in the 1990s to develop numerical avalanche forecasting systems and expert systems, particularly in Europe (Bolognesi et al. 1992; Giraud 1992; Schweizer and Fohn 1994; Gassner et al. 2000). Expert systems are the way of the future and will offer, in time, important backup and guidance to persons responsible for managing avalanche risk in the forestry sector. However, an expert system or other computer-based method is heavily reliant on the quality and quantity of the data that it uses. Such systems cannot replace the judgement and skill of the experienced avalanche technician.

5.4 CLASS III DATA: WEATHER OBSERVATIONS

Instrumentation required to obtain a complete weather record includes:

- maximum and minimum thermometers (or a single max-min thermometer) in a Stevenson screen (a standard, white-painted, ventilated enclosure)
- hygro-thermograph (which records air temperature and relative humidity on a paper chart)
- weighing bucket precipitation gauge (filled with an antifreeze mix)
- manual rain gauge (used when rain is likely)
- two snowboards and a ruler
- a total snow depth stake
- barograph or barometer

Barometric pressure, relative humidity, and precipitation gauge observations may be omitted in less avalanche-prone areas to lower the instrumentation cost and simplify the observations.

Just as with forest fire weather data, it is important to obtain daily observations whenever practicable. Each record should be complete. Missing observations and long gaps in the record reduce the predictive value of the data.

Basic avalanche observations should be made concurrently with weather observations. If avalanches fall onto any forest roads, the length of road affected, the kilometre point, and the deposit depth (measured at the centre of the road) should be recorded.

Avalanche occurrences should be noted with each weather observation. This practice can prove very useful should there be a need to cross-check weather and avalanche data. Relating weather and avalanche occurrence data is the foundation of numeric avalanche forecasting (McClung and Schaerer 1993, p. 164; McClung and Tweedy 1994).

The Canadian *Observation Guidelines and Recording Standards for Weather, Snowpack, and Avalanches* allows for a moderate degree of flexibility with regard to the choice of parameters observed, but requires that each parameter be observed in a consistent manner and recorded using a standard notation (CAA 1995).

Weather data are the easiest parameters to obtain. Basic weather observations (including observations of snowfall and snow surface condition) should be made early each day, ideally at an elevation close to the avalanche start zones or at steep, snow-covered work sites. Temporary observation sites established on log landings work well (Figure 125).

Weather data should be relayed by radio to a central point where they may be plotted on a simple, time-series profile on graph paper so that an ongoing record of conditions is available to the person responsible for avalanche risk management.

If weather conditions change markedly during the day (in winter, this may mean the onset of heavy rain or snow, or in spring, a rapid rise in temperature), then a second "interval" observation may be made.

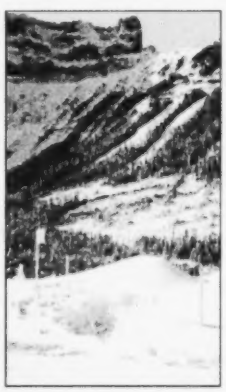


FIGURE 125
A simple, temporary weather observation plot established on the edge of a landing. A max–min thermometer is housed in a white-painted, well-ventilated screen. A snowboard (a square of white-painted plywood with a 1-m vertical-locating rod in the centre) is sited on the snow surface. A metre ruler is used to measure the depth of new snow each day. A separate stake is used to measure the total depth of snow on the ground.

An example of a field notebook page is included to illustrate a typical set of weather observations appropriate for a forestry operation in an avalanche-prone area (Table 24). Fewer parameters may suffice in some areas.

TABLE 24 *Typical observations of weather, snow, and avalanche data (After CAA 1995)*

Location	CP 43 Block 2, Landing on road 110.3, Elevation: 1450 m					
Observer	R.M.	R.M.	K.E.L.	K.E.L.	K.E.L.	K.E.L.
Date	000208	000209	000210	000211	000212	000213
Time, Type (Std, Int)	0700, S	0600, S	0700, S	0640, SI	0600, S	0700, S
Sky Condition	O	⊗	- ⊕	⊕	⊕	O
Precipitation Type/Rate	Nil	S-1	S1	S3	RL	Nil
Max Temp (°C)	-2.5	-3.0	-3.0	-1.5	1.0	0.0
Min Temp (°C)	-7.0	-6.0	-4.5	-4.0	-4.0	-11.0
Present Temp (°C)	-6.5	-3.0	-4.0	-1.5	0.0	-10.0
Thermograph (°C)	-7	-3	-4	-1	-0	-10
Thermograph Trend						
Relative Humidity (%)	78	86	96	98	100	67
New Snow (cm)	0	0.1	10	12	15	14
Storm (cm) (C = cleared)	0	0.1	10	20	21	19, C
Snowpack (cm)	123	122	131	139	141	139
Rain Gauge (mm)	–	–	–	–	3	–
Precip Gauge (mm)	60	60	67	77	82	82
Foot Penetration (cm)	37	35	43	52	51	45
Surface Form/Size		PP, 0.3	PP, 0.3	PP, 0.3	DF, 0.3	DF, 0.3
Wind Speed/Dir	L, E	Calm	M, SE	L, S	L, SW	M, E
Blow Snow Extent/Dir	Nil	Nil	Nil	M, S	Prev	U
Barometric Pressure (kPa)	104.5	103.0	100	99.6	101.0	102.6
Comments					Rain gauge frozen	
Avalanches (Type/Size)	0	0	0	0	S2.5	L1
Depth on Road (m)					1.2	
Length of Road Buried (m)					45	

Permanent Weather Stations

Ridgetop locations are best for measuring wind and free air temperature (Figure 126). High-elevation ridges are harsh environments where instruments are often subject to extreme rime ice accretion, lightning strikes, and ground surges. Careful selection of any weather station site is important for data to be representative of conditions in the area (Tanner 1990).

International standards and conventions relating to sensor exposure and ventilation should be followed (World Meteorological Organisation 1983). Maintenance of a standard sensor height is difficult, if not impossible, because of the variability in depth of the winter snowpack. When mounting most sensors, higher is generally better (except for precipitation measurement), with 10 m being a common standard.

FIGURE 126 *Mountaintop remote weather station used for avalanche forecasting. Parameters measured are wind speed and direction (an alcohol spray inhibits rime ice build-up on the anemometer); air temperature and humidity (in a radiation shield); and snow depth (with an ultrasonic range finder). Snow temperature sensors are spaced on the white pole at 10-cm intervals (to derive temperature gradients within the snowpack).*

Capital costs for an electronic weather station capable of operating at high elevations throughout the winter are considerably greater than for a typical forest-fire weather station, as additional expenditure is required to assure continuous winter operations. Maintenance costs of ridgetop electronic weather stations can be high because of the need to regularly restock alcohol-based antifreeze systems used to de-ice anemometers. Access in winter is generally only practicable by helicopter.

Sheltered mid-slope locations are far superior sites for measuring snow accumulation, precipitation, and snowpack temperature parameters. Operating costs are lower at such sites. Air temperature measurements made at mid-slope sites can often be extrapolated upslope to estimate air temperature conditions at the avalanche start zones through the application of the average environmental lapse rate (0.6°C per 100 m vertical). In areas subject to fluctuating freezing levels (e.g., the Coast Range), hourly data from a mid-slope station are very useful for forecasting direct-action avalanches. Hourly data may reveal critical trends (such as precipitation intensity) that are smoothed out in daily summaries.

Valley sites are convenient locations to measure precipitation, but it must be remembered that precipitation can increase exponentially with elevation

(Figure 127). Snow loading in avalanche start zones can be seriously underestimated if observations made in the valley bottom are considered representative of those occurring at higher elevations.

FIGURE 127 *Lower-elevation weather station adjacent to a road in avalanche terrain. Manual observations from snowboards give height, density, and water equivalent of new snow. Automatic measurements are made of air temperature and humidity and total snow depth. Precipitation is measured in a standpipe (700 mm capacity) containing glycol and alcohol, which is mixed with a pump.*

Near real-time data from remote weather stations can be readily processed by a computer and presented graphically, which enables skilled avalanche forecasters to readily identify trends that could give rise to increased avalanche risk (Figure 128).

5.5 MOUNTAIN WEATHER FORECASTING

Maritime weather systems move over the west coast of North America, often with very strong dynamics, leading to intense periods of precipitation and fluctuating freezing levels. In the coastal snow climate, these systems can produce rapidly deteriorating snow stability and "direct action" avalanche cycles, particularly during rain-on-snow events (Conway and Wilbour 1999).

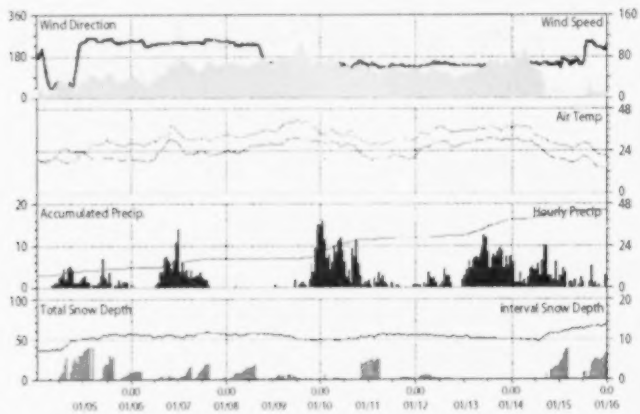


FIGURE 128 *Time-series plot of weather data used in avalanche prediction. Plots (top to bottom) are:*

- *Average wind direction and speed, and maximum gust*
- *Air temperature from two stations of different elevation*
- *Hourly and accumulated precipitation (measured in a standpipe storage gauge)*
- *Hourly and total snow depth*

(Source: Judd Communications, Utah)

As weather systems encounter successive mountain ranges across the province, they become modified, resulting in progressively lesser precipitation and colder temperatures.

In the interior ranges, snow stability tends to change less quickly, since it often depends on loads applied to weaknesses buried deep within the snowpack. These weak layers may linger, producing persistent instabilities that last for months, or even a whole winter season (Jamieson 1995; Davis et al. 1997; Jamieson and Johnston 1999.)

Regardless of the snow climate, changes in snow stability are brought about by the influence of weather. Just as with weather prediction for forest fire danger rating, accurate weather forecasts are important for avalanche prediction.

Conventional weather forecasting now uses General Circulation Models (GCMs), which run on a global domain to deliver accurate synoptic-scale forecasts (analyzing features with dimensions in the order of hundreds to thousands of kilometres). Under certain circumstances, these forecasts may be accurate at ranges as long as 5–7 days (Figure 129).

In the past decade, meso-scale weather forecasting (of features with dimensions in the order of tens to hundreds of kilometres) has increased in accuracy and resolution (Roeger et al. 2000). A meso-scale model is a physical simulation of the atmosphere. It runs over a limited domain, but with much higher resolution than a GCM, and incorporates a digital terrain map as its bottom boundary. The model output is analyzed by a meteorologist with experience and skill at forecasting for the local terrain. This enables accurate forecasting of meso-scale features that may have life spans as short as 3 hours. The maximum temporal scale for meso-scale forecasting is about 48 hours.

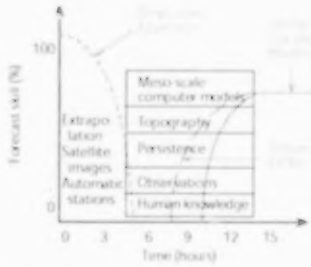


FIGURE 129 *Spatial and temporal scales of various weather forecasting techniques. (Weir and Auer 1995)*

The meso-scale technique has specific limits in both temporal and spatial scales and, to date, cannot accurately predict the location or precise timing of very small-scale features. However, the chance of a meso-scale

meteorological event (such as the development of a convective precipitation cell) occurring over some time within an area can be accurately inferred from the model output.

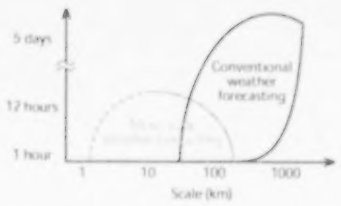


FIGURE 130 *Predictive skill associated with meso-scale forecasting technique compared to traditional approaches. (Weir and Auer 1995)*

True meso-scale forecasting is not yet widely practised in North America, but holds promise for those engaged in avalanche safety and control operations (S. Walker, meteorologist, MoT Snow Avalanche Programs, pers. comm.). The technique will help close the gap between short-term forecasts (made through observations and extrapolation techniques) and synoptic-scale forecasts based on GCM and other computer model outputs (Figure 130).

5.6 AVALANCHE CONTROL

Good forest development planning and prudent scheduling can minimize the amount of avalanche control necessary in forest operations. However, if winter harvesting of steep terrain coincides with an unstable snowpack and a high snow supply year, then avalanche control will be necessary.

Passive and Active Control

Passive avalanche control involves avoiding areas that have the potential to generate avalanches (i.e., areas where unstable snow exists on steep slopes). The ultimate, safe, passive control procedure is to postpone harvesting and other operations until early summer.

Active avalanche control in a forestry situation normally involves delivering explosive charges to a slope (e.g., through helicopter bombing of open slopes or case-charging steep cutbanks on roads), with the objective of triggering an avalanche. Ideally, all unstable snow will be removed from the path. Different approaches may be necessary when dealing with existing avalanche paths as opposed to new avalanche-prone terrain created by clearcut harvesting.

Persons undertaking avalanche control must have current blasting certificates endorsed for the use of safety fuses in avalanche control.

Specific endorsements are required for cornice blasting, hand-charging, and helicopter bombing. Electric detonators are not used because of the danger of accidental initiation by static electricity fields, commonly associated with blowing snow. A variety of explosives are available, each producing different effects in snow (Johnson 2000). The typical size of a charge ranges from 1 to 25 kg.

Consider the Outcome

The preferred philosophy for active avalanche control is to bomb a suspect slope whenever there is significant new snow loading above a recognized weak layer. In a forestry context, bombing may be delayed until a weak layer develops in the snowpack above the height of tree stumps with intact rooting systems (i.e., for species other than cedar, stumps may offer protection for 5–15 years after harvest; rot sets in thereafter).

The objective of regular explosives-based control work is to produce small avalanches that do not run the full length of any existing path (and implicitly do not extend the boundaries of existing avalanche paths by causing damage to intact forest downslope).

This operational philosophy may not be applicable in a steep cutblock—that is, a block set out in terrain steeper than 30° (60%), with long continuous slopes above mature forest—as the entire block may represent a start zone. The potential exists to destroy forest below the downslope timber harvest boundary.

Bombing above Standing Forest

Releasing an avalanche in a clearcut where there is more than 100 m in slope distance and no lower-gradient terrain at the bottom of the block will likely enable an avalanche mass to accelerate and gain sufficient momentum to damage any forest downslope.

The critical slope distance that an avalanche mass runs to gain sufficient momentum to penetrate downslope forest depends on the interaction of a number of terrain and snowpack variables. No method currently exists to quantify this distance, but there are examples of timber destruction that clearly demonstrate that the slope distance is less than 150 m. Critical slope lengths cannot be specified at this time.

When, and When Not, to Trigger Avalanches

Experienced avalanche technicians are trained to predict weather periods that will lead to the development of unstable snowpacks. By monitoring weather

forecasts and weather observations, technicians can recognize the optimum time to undertake avalanche control. However, the objectives of sustainable forest management may present a range of issues that are unfamiliar to an avalanche technician who is new to the forest sector.

If a substantial slab has built up over a weak layer deep in the snowpack on a steep slope, then any avalanche might lead to significant losses if mature timber or new plantations exist downslope. Artificially triggered avalanches may run much farther than expected. Machine costs for avalanche debris removal can be very high if a long length of forest road is buried to a depth of more than 2–3 m. However, if workers or others must access the area, then safety must take priority.

A less risky management option, and perhaps a lower-cost one, may be to use passive control; that is, cease operations and pull out of the area until snow stability improves. In extreme cases, it may be safe to resume work in an area only after spring break-up. If conditions are near critical (i.e., snow stability is poor or very poor and the load on a weak layer is considerable), then personnel should not enter the area and equipment in the area should not be moved until conditions improve.

Interpretation of Bombing Results

When very few releases are produced on a control mission, it may indicate that shots were poorly placed or that the timing was off. It does not necessarily indicate that the snowpack was inherently stable.

Mistiming of bombing can lead to a false sense of security. Bombing after the "window of opportunity" has passed may produce no results (there is an optimum time for avalanche control, particularly in the Coast Range, where new snow rapidly gains in strength). However, bombing that produces no results does not necessarily mean that the situation is safe. The snowpack may become unstable again following the next increase in load (from new snowfall or rain), any reduction in strength, or an increase in stress at a weak layer (this could be produced by a variety of factors).

Bombing can also be used to test the hypothesis that the snowpack is indeed stable (LaChapelle 1980). No releases may be a satisfactory result in this circumstance. Management commitment should be obtained when this approach is employed; however, this practice can be perceived as an expensive treatment that produces no results.

Consider the Runout, Consider the Consequences

The consequences of avalanche runout must be assessed for each block where control is contemplated. If a large mass of snow is released, will it stop before reaching the bottom of the block? A Size 3 or larger avalanche on a steep, open slope may stop only if there is a significant reduction in the incline of the path. High stumps or individual trees will not stop a mass of snow once it is in motion. Channelized avalanches can flow a long distance once they enter a gully.

The following points should be addressed:

- If the avalanche does not stop, might the impact pressures be such that standing timber below the block will be damaged?
- Is there a building, fish stream, water intake, forest road mainline, highway, railway, power line, or other utility in the runout zone?

The term "avalanche control" is perhaps a misnomer. Even experienced avalanche workers are often surprised by avalanche behaviour in both the start zone and in the runout. Once a large avalanche is in motion, there is little control. No one can be absolutely certain as to where it might stop. Many experienced practitioners of avalanche control have made the comment "I've never seen it do that before." Practitioners learn to expect the unexpected.

Elements at Risk

An avalanche atlas of all known and potential avalanche paths should be completed. The atlas should list the elements at risk in or below each avalanche path. The potential consequences of a large (climax) avalanche should be rated for every path. An avalanche atlas is a necessary foundation for risk management in snow avalanche–prone terrain (Fitzharris and Owens 1983).

Helicopter Bombing

Helicopter bombing is a very effective way to test and release unstable snow without exposing workers to an avalanche hazard (Figure 131).

The pilot is the key player and has overall command in any helicopter bombing mission. It is recommended that the pilot be confident, accustomed to winter conditions, and familiar with the area. The crew must never pressure the pilot to ascend above the treeline in whiteout conditions or to take any other unnecessary risk.

Rules of Thumb

With respect to avalanche initiation and runout, keep in mind that it is often the exception to commonly accepted "rules of thumb" that leads to incidents and accidents.

The pilot must be familiar with Workers' Compensation Board requirements and the operator's approved helibombing procedures (Appendix 1). The helicopter's owner must have Transport Canada approval for the carriage and delivery of explosives.

FIGURE 131 *Explosive charges are delivered by helicopter to start zones to trigger avalanches. Example shows double-fused primer to minimize the possibility of a dud.*

Emergency procedures, to be followed in the event of a machine malfunction, must be developed and practised. There will be little opportunity to jettison a full payload of bombs in an emergency, but the pilot may instruct that primers armed with detonators be jettisoned from the craft. Note, however, that the pilot may not want any objects to be thrown from the craft in an auto-rotation descent for fear of a rotor strike. All scenarios must be planned for and discussed with the pilot prior to take-off.

FIGURE 132
Local experience helps in the identification of preferred targets, which should be recorded in an avalanche atlas of the area.

NOTAMS

If the operating area is on a tourist, heliski, or other flight route, the pilot should seek authorization to issue a NOTAMS (Notice to Airmen) and attempt to secure the air space.

Generally, the objective is to bomb when instability is at a maximum. Avalanche control crews will need to move quickly to secure all roads in the area and sweep them before bombing. A spotter should be positioned in a safe location at either end of any road in the area being bombed. These spotters must be equipped with a radio on the same frequency as the helicopter.

The spotters have three key duties:

- To keep vehicles off the road (including winter recreationists).

Remote Triggering

When hard snow slabs exist, sympathetic releases may follow initiation of a single avalanche. Sympathetic releases may occur a kilometre or more from the triggering event. In some conditions, sympathetic releases may occur across a ridgeline in a completely different drainage. This possibility must be considered if explosives are used for avalanche control.

- To listen for other aircraft entering the area.
- To monitor the road and air traffic radio channels.

Most start zones have an area of maximum sensitivity or responsiveness to the detonation of explosives. These areas may be discovered only with experience, but a seasoned crew should be able to pick zones where stresses or accumulations are maximized. These areas become preferred targets that should then be documented in the avalanche atlas (Figure 132).

5.7 WINTER OPERATIONS

Harvesting Operations

Persons operating stationary equipment (e.g., yarders) located in avalanche paths may be exposed to risk for extended periods. Workers bucking logs on landings located in avalanche paths are more vulnerable than are workers inside machines. Safe sites should be identified for workers who are sharpening and fuelling saws. Maintenance work and lunch breaks should not be taken under steep cutbanks.

While machine cabs offer some protection, workers in them can sustain injuries from broken glass. Trauma and suffocation are also possible. In coastal Alaska, a 15 t (D-6) bulldozer clearing avalanche debris was swept more than 100 m by another avalanche. The machine operator was thrown from the cab and subsequently died of internal injuries (Anchorage *Daily News*, February 2000). Heavy machinery operators and truck drivers are not immune to the danger of avalanches (Figures 133 and 134).

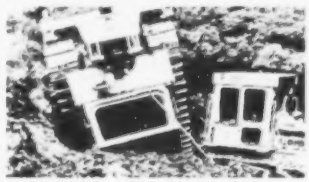


FIGURE 133 *An operator sheltering behind this bulldozer was crushed when an avalanche overturned the machine.*

FIGURE 134 *This loaded logging truck was hit by a Size 3 avalanche at Bear Pass near Stewart. The truck was stopped at the time because the road was blocked by an avalanche deposit on an adjacent path.*

Road maintenance staff, such as grader, bulldozer, and loader operators, are exposed to considerably higher hazard than are most others on forest roads. Operators are likely to be ploughing and grading during storms when the likelihood of a direct-action avalanche is greatest. The officer responsible for avalanche risk management needs to ensure that back-up communication systems are available for operators who work alone, especially outside normal operating hours.

Some forest companies fit graders with satellite phone systems and require scheduled check-in calls

during periods of moderate and high avalanche danger. However, reception can be poor in steep-sided valleys, so having operators work in tandem with line-of-sight radio communications may be a more practicable risk management system (G. Smith, RPF, Gilbert Smith Forest Industries, pers. comm.).

Recommendations for Safer Winter Operations

- *If an applicable regional avalanche bulletin declares a Moderate or Considerable avalanche danger for a given elevation, and if harvesting or other winter activities are underway in potential avalanche terrain and an operation has no formal system of assessing snow stability or avalanche danger, then it is recommended that weather, snowpack, and avalanche activity be monitored and recorded on site (as outlined in this handbook). Safe work procedures should be followed and outside expertise (e.g., an experienced avalanche technician with a CAA Level 2 qualification) consulted to assess the avalanche danger.*
- *If an applicable avalanche bulletin declares a High or Extreme avalanche danger in the region, then it is recommended that harvesting or other winter activities underway in potential avalanche terrain be terminated until such time as outside expertise can be retained to appraise and advise on the situation.*
- *If an operation does not have a suitably qualified person responsible and available for assessing the avalanche danger in winter, then it is recommended that harvesting in potential avalanche terrain be scheduled for a different time of the year when the risk of snow avalanches is low or non-existent.*

(Refer to Section 5.9 in this handbook and Appendix 3 for more information on regional avalanche bulletins.)

Recommendations endorsed by Workers' Compensation Board; authority: WCB regulation 26.18

Snowmobiles in Forest Operations

Forest layout technicians and others who work in remote areas in winter may be at considerable risk from avalanches, especially when traversing unploughed forest roads that cross through steep cutblocks. Buried surface hoar layers may create extreme avalanche dangers at elevations well below the timberline. Evidence of avalanches (or not) in alpine areas may not be indicative of the situation within lower-elevation cutblocks. The snow stability may be such that an additional trigger such as a snowmobile may release a large avalanche.

Workers who use snowmobiles to access work sites in winter should be trained in backcountry rescue and safe travel procedures (such as not

travelling alone; not crossing through cutblocks in groups). Each snowmobile should carry a rescue shovel and probe. Good training resources include the book *Sledding in Avalanche Terrain* by Jamieson (1997) and the U.S. Forest Service video "Riding Safety in Avalanche Country." These are available from the CAA.

At least one transceiver manufacturer produces a transmitter that operates on a secondary frequency for recovery of snowmobiles.

Removal of Avalanche Debris on Roads

FIGURE 135. *Avalanche debris removal in Galena Pass near Trout Lake. Operators must not leave a slot where vehicles or workers could be trapped if a second avalanche were to occur.*

Operators must be instructed to never leave a slot cut through avalanche debris, as these can trap equipment or workers should a second avalanche descend the path. All slots must be "daylighted" on the outer edge—that is, material should be pushed well off to the side (Figure 135).

Crews clearing debris from forest roads in an avalanche path with multiple start zones, or where only a section of a start zone has released, can be at considerable risk. An experienced avalanche technician (i.e., a person with a CAA Level 2 qualification and who has a Workers' Compensation Board certification for explosive use) must ensure that crews will not be exposed to any unacceptable risk. If there is a potential for additional avalanching, snow above the road should be bombed or road clearing operations postponed. If the avalanche danger is assessed as moderate, it may be acceptable for clearing to begin, provided that safe work procedures are adopted. In this case an assistant, equipped with a radio and familiar with avalanche rescue procedures, must remain off-site to act as a spotter. It may be acceptable to have two machines clear avalanche debris in adjacent paths without a spotter, provided that the operators have appropriate rescue training, maintain visual contact, and observe regular (15-minute) radio checks with their operating base. Avalanche debris should not be cleared at night because it is not possible to monitor start zones.

When debris removal is underway, one person with access to a phone system (typically a radio dispatcher or scale operator) must monitor radio traffic. That person must be familiar with the written avalanche rescue plan and have access to an up-to-date list of resources and rescue agencies (see Appendix 2).

5.8 AVALANCHE RESCUE

A discussion of avalanche rescue techniques is relevant for operators who undertake winter harvesting.

Rescue Transceivers

Three items are essential to facilitate the quick recovery of any person caught in an avalanche:

- Shovel
- Probe
- Rescue transceivers (avalanche rescue beacons)

Where the risk warrants, these three items of personal protective equipment (PPE) should be issued to field workers in winter and recalled at the end of the avalanche season.

All electronic avalanche rescue transceivers in use today operate on 457 kHz. Older, alternative frequency beacons must not be used.

The International Commission on Avalanche Rescue has published results of extensive field tests conducted with various makes of rescue transceivers (IKAR 1998). For all makes, experienced rescuers were able to locate the buried transceivers quickly, with search times ranging from 2 to 3 minutes, but considerable differences were noted in the receiving range of various makes and models (20–45 m). When several rescuers are systematically working through an area, it is important that they be spaced so as to not miss a buried victim. Optimum spacing depends on the make of transceiver in use.

Some newer-model transceivers use digital technology and come with optical range indicators that greatly assist rescuers not familiar with the transceiver search techniques (Figure 136).

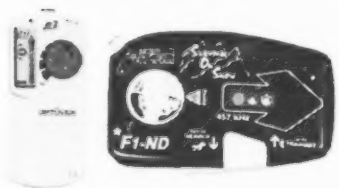


FIGURE 136 *Typical rescue transceivers. Model on left has optical range indicator.*

Workers operating in high-snowfall or high-hazard areas should wear these devices at all times. It is important that the beacons be switched on and checked before the user leaves camp or home in the morning. Transceivers should not reside in a lunch box, toolbox, or vehicle glove box or door pocket.

Some machine operators and fallers prefer to wear transceivers in a secure pouch on their belt rather than around their neck. This is acceptable as long as the instrument cannot be torn off should an avalanche strike the wearer. Transceivers should not be worn externally. In cold conditions they should be worn close to the body, to keep the batteries warm.

Of course, speed in transceiver searching does not guarantee quick recovery. Probes must be used to locate a deeply buried victim and these are seldom longer than 3 m (Figure 137). Thus, any victim buried at a greater depth is unlikely to be found without rescuers resorting to digging a trench and then re-probing the area. Digging to a depth in excess of 3 m takes considerable time.

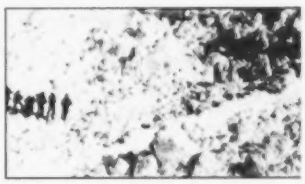


FIGURE 137 *Searchers probe a Size 5 avalanche for a victim who was not wearing a transceiver. Depth of burial exceeded the length of probes. The victim was not found by probing.*

Workers should train to locate two avalanche transceivers buried just below the snow surface in a 30 × 30 m area within a 5-minute period. Transceiver rescue practices can be undertaken by different crew members at the start of work or after a break each day. Crew supervisors, as part of an operation's ongoing quality safety management system, should maintain a training log showing times for successful recoveries.

Loss Control

Ensure that the buried transceivers are turned on and set to transmit before undertaking search exercises. Beacons not turned on, or not turned to transmit, have been lost during practice sessions.

One transceiver can be permanently located at a convenient site (such as the administration office or camp cookhouse) to enable personnel who work alone (e.g., grader operators) to check that their own transceiver is operating. Workers should be advised that this transceiver could be signed out if they should forget to bring their own unit to work. Furthermore, workers must be made aware of the folly of not wearing a functioning rescue transceiver when entering or working in a known avalanche area after the snow depth reaches the avalanche threshold.

Wearing avalanche transceivers promotes avalanche awareness. Workers must appreciate that their best hope of rescue comes from their immediate co-workers. All workers need to be able to rely on their co-workers to keep their transceivers in good working order and to become proficient in their use. According to Jamieson and Geldsetzer (1996, p. 19) "Recovery

of victims within 15 minutes of burial is critical." If an avalanche occurs there will be no time to go for help.

If avalanche paths intersect forest roads, then all field staff travelling on the roads should wear avalanche rescue transceivers when the avalanche danger is above low. Grader operators should wear transceivers at all times.

Wearing a rescue transceiver does not guarantee survival in an avalanche. It offers no protection against trauma from impact with trees in a moving avalanche or from suffocation. It does, however, greatly expedite the recovery of a buried avalanche victim and reduces the dependence of the crew on external agencies or groups for avalanche rescue. Work crews should be made aware that they are in a backcountry situation and that they must be self-sufficient in avalanche rescue capability. Self-sufficiency will create a huge saving in time that greatly increases the chances of live recovery. Reliance on outside agencies or distant work crews offers little hope of live recovery for workers caught outside of machinery or vehicle cabs.

Transceiver Care and Maintenance

Rescue transceivers are hardy but not indestructible. Workers need to know that transceivers will not stand up to harsh treatment such as being dropped or immersed in water or other liquids. Battery life generally exceeds 200 hours. Supervisors should schedule battery changes as appropriate. Spare batteries should be available in case a transceiver is left on and the batteries drain. Most transceivers have a battery test mode; workers should check the battery level each day and develop the habit of testing both the "transmit" and "receive" mode of each other's transceiver.

At the start of each winter season, new batteries should be installed and both the "transmit" and "receive" function of every transceiver tested. The maximum range of each device should be recorded in a log book. Batteries should be removed from all transceivers at the end of each season.

Forest companies may choose to loan or rent rescue beacons to contractors who will be travelling through or working in avalanche-prone areas. This places an onus on the company to ensure that the device is operating correctly and that appropriate training is given in the use of the device. A small illustrated leaflet, preferably printed on a waterproof card, showing safety tips and describing rescue techniques should be issued with each transceiver.

Workers who undertake outdoor winter recreation, such as snowmobiling or backcountry skiing, will likely be eager to use their beacons during time off. This should be encouraged, as it helps build proficiency and elevates awareness of avalanche safety issues.

Transceiver Searching by Helicopter

Local helicopter pilots should be trained in the use of rescue transceivers. A beacon, set to "receive," can be taped to the helicopter's skid with an extension earphone connected to the pilot's helmet (Weir and Carran 1997). Experience has shown that pilots proficient in tracking radio-collared wildlife need very little instruction in avalanche search technique. It is far more effective to have the pilot conduct the search than have a passenger direct the pilot.

Helicopter-based transceiver searching is particularly effective on large avalanches or where debris consists of large blocks or slick icy surfaces (Figure 138). In situations where it is difficult to traverse the ground, searching on foot or with snowshoes can be slow. This is particularly so when analogue transceivers are in use because searching with these devices relies on a change in signal strength. By flying at moderate speed over the area, the pilot can very quickly focus on the point of maximum signal strength.

FIGURE 138 *Large, blocky avalanche deposit 500 m downslope of the spring snowline. Searching on foot in such material is slow and very difficult. Long steel probes would be required. Helicopter-based transceiver searching is much more efficient, especially on large deposits.*

When more than one person may be buried, the pilot can drop off a single searcher at a point of maximum signal strength to complete the pinpointing phase of the search. The pilot can then proceed to locate other buried victims and drop other searchers as appropriate. Each searcher requires a transceiver, a probe, and a shovel, and should be equipped with a radio set to the helicopter's channel. The helicopter would then transport other rescuers with shovels to the burial sites. While the recovery is under way, the pilot should prepare to fly victims off-site.

Training

Crews, equipped with shovels, should have practised hover exits and entry procedures in low-stress situations. A hover entry is difficult to undertake in a heavily loaded, two-bladed helicopter (e.g., a Jet Ranger).

Alternative Rescue Systems

An alternative avalanche victim location system is available, but it relies on external help to facilitate a rescue. This system uses a low-cost, passive reflector mounted on an adhesive patch that can be attached to an article of clothing, belt, or similar item. The reflector is a rugged, small device (60 × 23 mm) that requires no battery, so it should last for an extended period. However, the functionality of each reflector should, at a minimum, be tested at the start of each winter. Two reflectors are recommended per person to give some redundancy.

FIGURE 139 *Searching with a detector device.*

The system operates via directional radio searching and has a maximum range of about 200 m (Figure 139). The radio detector is generally brought to a site by helicopter.

Several ski areas in British Columbia own or rent the search detector device (an updated list is available online at www.recco.com). To facilitate a good chance of live rescue, the detector unit needs to be based within 15–30 minutes flying time of any exposed work site.

This rescue system can be used as a backup, but the detector device needs to be close at hand and radio communications must be reliable (i.e., workers must have access to the local heliski or ski area's rescue frequency). The system is appropriate for use by logging truck drivers who may rarely be exposed to an avalanche hazard and who are afforded some protection by their truck cabs.

FIGURE 140 *Avalanche debris removal in Bear Pass near Stewart. Some road authorities fit reflectors to vulnerable infrastructure such as bridge abutments to facilitate location so as to avoid machine damage when clearing avalanche debris.*

Some agencies have attached the reflectors to bridges, small items of equipment, or other assets that might be buried by avalanches (Figure 140).

Rescue Caches

A simple rescue cache should be readily available at work sites in avalanche terrain. A cache should typically consist of a dozen 3-m-long probe poles, a 10-mm (⅜ inch) diameter steel rod with a 300-mm-long handle bent at a right angle at one end, and two sturdy square-mouth steel shovels.

The cache should be clearly marked and stored beyond the edge of the block, out of any potential avalanche runout. It can be carried in a crew vehicle, but the vehicle must never be parked in or below an avalanche path.

First aid equipment, blankets, a backboard, and flashlights should also be available (see Appendix 2).

Rescue Exercises

A full-day avalanche rescue exercise should be conducted each winter. Such an exercise should start with a review of the company's formal written rescue plan (see sample in Appendix 2) and include instruction or refresher training in the use of the rescue transceiver and other techniques.

The company safety supervisor or officer responsible for avalanche risk management should set up a realistic simulation exercise. This provides an opportunity to test written plans and familiarize office staff with rescue procedures.

Workers should be required to search for buried transceivers in actual avalanche debris, as well as to form a probe line and practise formal rescue techniques. Rescue transceivers can be fitted to one or more mannequins, which are then buried at various depths in the snow. (Mannequins can be easily made from a set of heavy winter coveralls stuffed with rags.)

5.9 INFORMATION EXCHANGES AND AVALANCHE BULLETINS

Forest operators who share terrain with heliski companies may benefit by negotiating an arrangement to receive regular snow stability assessments and avalanche forecasts from the snow safety officer or guides employed by these companies.

Logging operators are encouraged to join the CAA's information exchange (INFOEX) when winter harvesting is taking place in potential avalanche terrain. Participants share weather, snowpack, and avalanche observations and snow stability assessments with one another in a confidential environment that aims to benefit all members. The daily INFOEX bulletins contain a technical discussion that rates the snow stability on a scale from Very Good to Very Poor (Appendix 6).

In the absence of better information, a regional assessment of avalanche danger provides guidance as to when to apply appropriate work procedures or when to seek assistance with avalanche management (see Appendix 3 for a list of service providers). Currently, a five-step classification is used to rate the avalanche danger (*Low*, *Moderate*, *Considerable*, *High*, and *Extreme*).

Operators should be familiar with the information provider's disclaimer. Most providers explicitly state that their bulletin is intended for recreationists and not for commercial operators. Operators must realize that weather, snow, and avalanche phenomena all display great spatial and temporal variability. The information is given in good faith and the provider cannot be held responsible or liable for unforeseen outcomes.

It is important to note that:

- Not all of the province is covered by avalanche advisories.
- Some advisories are not prognostic (rather, they give only an assessment of the current danger; they do not predict future trends).

Case studies of risk assessment

6

Case studies are instructive in an analysis of avalanche risk. Several of the following summaries were produced in conjunction with an avalanche workshop held in Revelstoke in 1996 (Stethem et al. 1996). Examples cover a range of incidents in varied terrain and conditions. In Case Study 6.7, the incidents described resulted in a heightened avalanche awareness and in the development of a set of safe work procedures.

6.1 WARDANCE SLOPE AT BIG SKY, MONTANA

A 35–40° (70–80%) slope was logged for a ski run in the 1980s, creating a 1-ha start zone (Figure 141). Avalanches threatened four lots in a subdivision downslope and legal action ensued.

The range of mitigation measures proposed included:

- deflecting or arresting dams;
- incorporating protective structures into the buildings;
- using zoning to prohibit the use of the buildings during the winter; and
- constructing snow-supporting structures in the start zone to promote reforestation of the slope.

A snow support structure was chosen, designed, and constructed with the help of American and European avalanche consultants. The structure and its foundation had to be designed to cope with snow creep and glide pressures, which can be significant.

FIGURE 141
High consequence: a slope logged to create a ski run has potential to generate avalanches that might run out into high-value buildings below.

This design was based, in part, on a 20-year reforestation period (Figure 142). Since its construction in 1990, several small avalanches have initiated below the structure. One larger, full-depth release occurred to the right of the structure, but did not come close to the remaining trees below the slope. It did not pose a threat to the subdivision.

FIGURE 142 *Supporting structures in start zone designed to inhibit avalanches, thus protecting buildings and people in the runout zone.*

FIGURE 143 *Ten-year-old trees, 1.5–2 m in height, offer little protection in a 1.25-m-deep snowpack.*

The support structure and reforestation, though expensive, were considered the best solution for long-term mitigation of the hazard to the lots. Reforestation of the avalanche path was seen to be the most practicable and effective means of reducing the avalanche risk. Reforestation now depends on the successful functioning of the engineered snow support structures (Figure 143).

6.2 PROTECTION ROLE OF FORESTS ABOVE THE COQUIHALLA HIGHWAY, B.C.

Forests adjacent to the Coquihalla Highway contain valuable timber. Areas of forest adjacent to the highway have also been identified as having a "protection" function; logging these areas would increase the avalanche hazard on the highway. The B.C. Ministry of Transportation has long been concerned that logging of the slopes adjacent to the highway could increase the avalanche and debris torrent hazard.

The value of timber that could be harvested from these protection forests over 25 years was compared with the cost of additional avalanche hazard mitigation under four different scenarios (Lister et al. 1986):

1. No logging
2. Logging using conventional clearcut techniques
3. Logging with some restricted areas
4. Logging with careful controls

Option 4, involving intensive forest management prescriptions, was recommended based on a cost-benefit analysis. This option was expected to increase harvesting costs by 60%, but would not require additional measures to mitigate the avalanche hazard to the highway.

Lister's report provides a cost-benefit analysis based on harvesting and mitigating avalanche hazards and an example of designation of European-style "protection forests" in British Columbia. This concept is developed in the proposed Canadian national avalanche mapping and zoning standards (CAA 2002; McClung et al. 2002).

6.3 AVALANCHE TRIGGERED IN CUTBLOCK KILLS RECREATIONIST NEAR SALMO, B.C.

In January 1994, a snowmobiler was killed in an avalanche in a clearcut near Salmo, B.C. Because many forests are too dense to be used for winter recreation, logged areas inevitably attract recreationists. Accidental triggering of avalanches is likely in some areas, especially where extensive surface hoar development is common (e.g., in the Columbia Mountains).

Forest development on public lands is undertaken differently in British Columbia compared with the U.S. Pacific Northwest. In British Columbia, the timber licensee locates and lays out cutblocks on Crown lands. Similar accidents have occurred in the United States where the U.S. Forest Service is responsible for locating and laying out cutblocks in National Forests, which are federal land. If a new block proved to be avalanche-prone, then the responsibility would lie with the government, not the timber company (S. Bones, U.S. Forest Service, pers. comm.).

As a general rule, the U.S. Forest Service does not place signage on forest roads to warn of avalanche hazards. Unploughed roads and unmaintained areas are not signed in any way during the winter. Avalanches are treated no differently than any other backcountry hazard situation. Backcountry users recreate at their own risk in U.S. National Forests. The situation is less clear where roads are groomed for over-snow winter use.

FIGURE 144 *Two wet snow avalanches originated in adjacent clearcuts in the same period. One of these reached Highway 6.*

6.4 RANCH RIDGE, NEAR HILLS, B.C.

On February 12, 1988, a snow avalanche from a steep clearcut in an area known as the Ranch Ridge ran into a steep gully (Figure 144). The avalanche contributed to a mixed snow avalanche and debris flow,

which then ran out onto Highway 6, 3 km south of the community of Hills in the Slocan Valley. The deposit at the highway was a mixture of snow, log debris, soil, and rock.

Reports from the time of the incident indicate that the event originated in the clearcut as a wet snow avalanche, which then knocked down trees below the block. The avalanche entrained both timber and soil in the gully and ran out at the highway as a mixed deposit. A second avalanche ran in an adjacent clearcut and gully, but did not reach the highway, probably because benched terrain in the runout zone caused the event to stop above the highway (Figures 145 and 146).

FIGURE 145 *The first of two snow avalanches originating in a clearcut stopped just before Highway 6. A second event blocked both the road and railway. (A berm has subsequently been constructed in the runout to protect the highway.)*

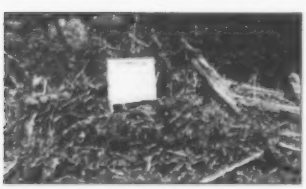


FIGURE 146 *Mixed deposit of snow, trees, and colluvium.*

A debris flow followed down the avalanche path in April 1988 when a landing failed. The flow probably entrained some of the avalanche debris already in the gully. The highway was again blocked and fine sediment was discharged into Slocan Lake. Further snow avalanches and debris flows have since occurred in the gully.

6.5 AIRY CREEK IN THE SLOCAN VALLEY, B.C.

At Airy Creek in British Columbia's Slocan Valley, a large, high-elevation clearcut (Cutting Permit 72, Block 6 in Tree Farm Licence 3) was logged in terrain that contained a shallow bowl and a small gully that extended downslope below the clearcut. Prior to logging, the potential for snow avalanches was limited to small, non-destructive events in the natural gully feature. After being harvested, the clearcut became prone to wind loading.

In February 1994, a large avalanche originated in the bowl within the clearcut. The avalanche entrained timber along the gully, breaking trees of up to 40 cm dbh. Midway down the track, mature cedar trees were ripped out of the ground in an area about 3 m wide by 10 m long (Figure 147).

One nearby cedar tree was flagged to a height of 15 m. The debris ran to the creek below, blocking the stream. Intakes on the community water supply were put at risk.

Regeneration of the forest cover in this new avalanche start zone and track is considered critical to the protection of downstream values.

Timber, soils, and surficial materials entrained in snow avalanches that run into creeks may affect both the water quality and supply of downstream communities. This site in the Slocan Valley has high scenic values.

FIGURE 147
Airy Creek avalanche originated in a clearcut and ran into a community watershed.

6.6 NAGLE CREEK CUTBLOCKS, NEAR MICA CREEK, B.C.

A series of clearcuts on a steep valley side were harvested in 1988 at Nagle Creek, near the Mica Dam, B.C. Replanting occurred in 1990. On March 14, 1996, a large (Size 4.5), wet avalanche released in Block 83D007-27, ran into standing timber below, and destroyed 12.5 ha of forest, a significant resource. Two adjacent blocks in near-identical topography did not avalanche (Figure 148).

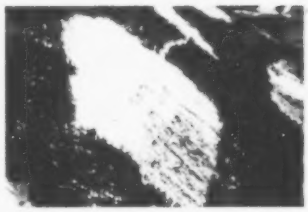


FIGURE 148 *The block in the foreground avalanched, but the two adjacent clearcuts, which have similar topography, were not affected. The affected block had been broadcast burned, which reduced the surface roughness compared with the unaffected blocks.*

Cutblock 83D007-27 measures approximately 500 m along the contour and has a maximum downslope length of about 500 m. It spans an elevation range of 950–1270 m (300 m vertical). The block has a slight convex profile with a narrow, gently sloping bench at the top. Below the bench, the slope is uniformly steep and has a number of shallow linear depressions and a few rock outcrops. Neither the bench nor the gullies are identified on 1:20 000 scale TRIM mapping.

Tree stumps of 0.2–0.8 m diameter and 0.3–1.0 m in height remained on the slope after harvest. Below the block, a continuous band of mature timber existed from 950 to 750 m elevation. A young plantation existed below 750 m (also see Figures 3, 17, and 85).

The avalanche fractured on a slope of 33–42° (65–90%), across a width of 500 m below a convex break in the slope where stumps were cut off near ground level to optimize deflection for cable yarding. A second, full-depth fracture extended across a steep section of road fill (Figure 149).

FIGURE 149 *Fracture occurred at upper convex slope change and below the road. A subtle concavity exists in a gully to the left.*

The moving avalanche mass was partly channelled by shallow depressions on the slope, which increased its destructive potential. Some surface materials and soils were removed below the cutblock by the moving avalanche (Figure 150). Avalanches stripped the bark and limbs on the uphill side of the standing trees (Figure 151).

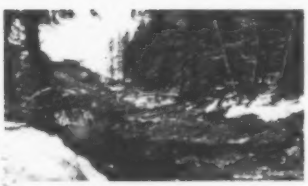


FIGURE 150 *Timber damage and soil erosion represent substantial resource losses.*

FIGURE 151 *Damage to immature trees in the start zone (snowshoe for scale).*

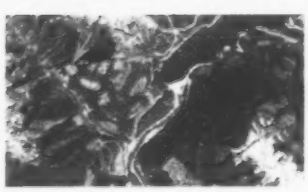


FIGURE 152 *LANDSAT image of the area surrounding Mica Dam showing forest damaged by avalanches at Nagle Creek (arrow). Note: An avalanche occurred in the block in March 2000.*

Similar destructive events also initiated in clearcuts at nearby Pat Creek, near Mica, and in the Akolkolex River south of Revelstoke during the same warm weather.

The Ministry of Forests retained an avalanche consultant to investigate the release. A snow profile investigation was undertaken above the fracture line and the snowpack was determined to be isothermal at 0°C. A hard melt–freeze crust at the surface was found to overlay a relatively low-strength snowpack.

A Ministry of Transportation remote weather station sited at a similar elevation and aspect approximately 5 km away showed a maximum air temperature of 13°C on the day of the event, up from the preceding day's maximums of 6 and 7°C. It is likely that rapidly rising air temperatures and strong inputs of solar radiation produced snowmelt. The avalanche release was attributed to liquid water percolating down to a series of crusts deep in the pack, producing a lubricated sliding surface.

The road through the block has subsequently been deactivated and the slope profile restored. Removal of the over-steepened fillslope is likely to have reduced the avalanche susceptibility in that part of the block.

The potential for forest regeneration has been compromised in parts of the block where soil was scoured. The affected area remains clearly visible from space in medium-resolution satellite images (Figure 152).

6.7 AVALANCHE IN A BLOCK WITH ACTIVE LOGGING, SOUTHERN INTERIOR, B.C.

Two avalanche incidents that occurred in an active harvest area in the Southern Interior of British Columbia in February 1999 provide insight into workplace hazards encountered during winter logging. Fortunately, no one was injured in the incidents. Avalanche awareness was much heightened and a set of safe work procedures developed. This case study is both real and highly instructive. After scrutinizing it in detail, one might be able assess how other operations would manage in a similar scenario.

After a series of snowfalls and a natural avalanche in an adjacent cutblock, two avalanche technicians were contracted by a timber company to assess the snow stability in a block where winter timber harvesting was approximately two-thirds complete (Figure 153). Their plan was to use explosives to release unstable snow if they assessed the snowpack to be unstable and the workplace hazardous.

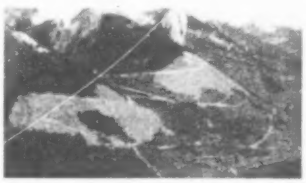


FIGURE 153 *A natural avalanche occurred in the cutblock at the right. Two avalanches were triggered in the cutblock in the foreground, one of which ran down to the creek in the valley floor.*

Day One – Accidental Triggering

Winter harvesting with partial suspension cable yarding was complete in the western half of a steep cutblock. The logged portion was separated from an access road approaching from the north by a 100–150 m long strip of immature forest. The eastern portion of the block had a forwarding trail crossing through standing forest to a cable yarder that was situated midslope in a partially harvested area. Harvesting and yarding in the upper portion of the block were complete. Both felled and standing timber were located below and adjacent to the yarder.

The logging crew consisted of five people in the harvest area and one on a landing. In the harvest area, one person was operating a cable yarder, and two were shovelling snow and felling and hooking trees onto the aerial cable. One person was unhooking trees at the yarder and another was skidding the logs down the forwarding trail to the landing. The person on the landing was bucking and loading logs onto trucks. Their employer was operating a grader a few kilometres away, ploughing snow from forest roads.

Two avalanche technicians arrived onsite to undertake a snow stability assessment. They determined that the yarder and crew were at risk if the slope above was to avalanche and recommended that the crew postpone

work until the snowpack stability could be assessed and, if need be, avalanches could be triggered with explosives. The contractor and logging foreman felt that, because of the recent yarding activities on the cutblock, snow accumulations would be inadequate to produce a substantial avalanche. The logging contractor and foreman decided that they would remove the crew from the work area if it were established that there was a potential instability in the snowpack. The avalanche technicians set out to make this determination through snowpack investigation. They had no clear authority to recommend that the logging operations be temporarily suspended.

Using skis fitted with climbing skins, the avalanche technicians climbed through the area of standing timber within the block. Their route proceeded westward towards an area where the slope broke into a stream gully and the standing timber met the uphill cable-harvested section. The size of the open slope (harvested area) between the climbing trail in the timber and the top road was considered to be sufficient to generate a large avalanche. The technicians decided that the rib forming the gully break to the west would make a safe climbing route so they continued their ascent to access the upper road.

When the avalanche technicians reached the upper road, they stopped to select a site to excavate a snow profile. The snowpack settled under their weight with a characteristic "whumpf." Immediately following the settlement, most of the snowpack on the harvested area on the eastern portion of the cutblock was set in motion. The settlement triggered a slab avalanche with a 30–40 cm deep crown extending from the technicians' climbing track to the gully near the eastern boundary, a distance of approximately 300 m. The fracture propagated across the entire area above the logging crew.

The avalanche ran through a stand of hemlock (age class 8, greater than 140 years old), burying the forwarding trail to a maximum depth of 4 m. It then ran out into the gully near the eastern boundary, burying much of the downed timber, then continued through standing forest, knocking down several large hemlock and pushing several trees down to the trail.

The logging contractor was notified of the situation by radio. He immediately made his way to the landing where the loader operator was working alone. The avalanche technicians made their way towards the yarder, prepared to initiate an avalanche rescue. They were extremely relieved to find four of the crew standing by the machine. One worker, who

sought refuge below the yarder, was partly buried as the moving snow flowed around the machine.

After establishing that the harvesting crew was safe, attention was turned to the skidder operator who had been forwarding logs down the trail at the time. The avalanche had travelled through the standing hemlock and over the forwarding trail. The technicians and harvesting crew followed the trail down to the landing, looking for signs of the machine. The operator had just reached the landing when the avalanche struck and was, fortunately, out of harm's way. It was quickly established that all workers were present and accounted for and that no injuries had occurred.

Some equipment (chainsaws, pulley blocks, and cables) was lost or damaged. The upper side of the yarder was buried to half the height of the cab and the operator had to climb out through the hatch in the top. The faller and shoveller working below the yarder were protected from the avalanche by the machine and the forwarding trail, which had absorbed some of the momentum of the moving avalanche mass.

After the event, a test snow profile was undertaken and the snowpack was found to contain a thin weak layer of surface hoar grains on top of the old snow surface, even though harvesting activities had disturbed the surface. The slope had been cross-loaded with new snow by winds from the west and southwest. Table 25 describes the avalanche start zone geometry and dimensions of the avalanche that released.

TABLE 25 *First avalanche start zone: geometry and dimensions*

Cutblock elevation	1450 m
Cutblock aspect	Northeast
Cutblock slope angle	53–70% (28–35°)
Avalanche crown width	300 m
Mass (estimated)	2400 t
Avalanche size	3.0
Avalanche trigger	Person, accidental

Day Two – Equipment Damaged during Avalanche Control

Given that the previous day's avalanche indicated very poor snowpack stability and that the avalanche technicians had found buried surface hoar, avalanche control work was planned.

The key area of concern was where a haul road crossed through a stream gully just before reaching a log landing. The gully showed evidence of previous avalanche activity: there was thick brush and only a few trees within 2–3 m of the stream banks. A reserve patch extended from the haul road, approximately 150 m up the stream gully, and was contiguous with standing timber on the east side of the gully. The reserve

timber and a strip of immature forest below the western portion of the block were presumed to be providing protection to the haul road where it entered the block from the north. In the harvested area above the reserve, wind-deposited snow had accumulated below a convex slope break. Because vegetation in the stream gully showed signs of past avalanche activity, the avalanche technicians decided to use explosives in an attempt to release the unstable snow at the gully to eliminate the hazard posed to the haul road.

A 25-kg explosive charge was delivered by helicopter to a cross-loaded slope above the reserve area with the aim of initiating an avalanche that would be confined by the gully. The fracture propagated more widely than anticipated and a Size 3 avalanche released. The slab pulled out most of the slope above the gully, but the avalanche did not become confined to the stream gully until below the haul road. The avalanche moved slowly as it ran through the reserve timber above the road, but rapidly gained speed within the gully. The avalanche track was widened as mature timber was broken along the flanks and the runout extended into a recently spaced juvenile stand. The avalanche ran to the edge of the creek below the gully, but did not enter it (Figure 154).

FIGURE 154 *New path resulting from slab avalanche triggered by explosives in clearcut above. The avalanche ran through the standing timber into the gully in the foreground.*

The contractor's emergency transport vehicle (ETV) was parked on an inactive forwarding trail, within the reserve timber patch, approximately 40 m west from the stream gully. There was approximately 30 m of standing timber above the vehicle. It was incorrectly presumed to be in a safe location.

When the avalanche ran through the patch of timber above the ETV, it buried the vehicle. The force of the snow then picked up the vehicle, spun it around through 90°, and deposited it wheel-side down on the main haul road approximately 10 m below. The avalanche continued down the gully to the edge of the creek, leaving the ETV on the road above. The vehicle suffered considerable external body damage including a broken window. It was excavated from the debris and driven away for repairs the next day. Had the road not stopped the vehicle, damage and retrieval efforts would have

been far more severe. Table 26 describes the start zone geometry and dimensions of the second avalanche.

TABLE 26 *Second avalanche start zone geometry and dimensions*

Cutblock elevation	1450 m
Cutblock aspect	North to northeast
Cutblock slope angle	53–70% 28–35°
Avalanche crown width	200 m
Avalanche fracture depth	40 cm
Avalanche size	3.0
Avalanche trigger	Explosives, by helicopter

Incident Review

No weather records were available. The avalanche technicians were not informed of the natural avalanche in an adjacent cutblock. Perhaps no one working onsite noted it.

When the snowpack stability in an area is unknown, it is better to work from the hypothesis that the area is highly unstable and take all practicable precautions. The assumption that recent partial suspension logging had disturbed the snowpack enough to obliterate any weak layers proved incorrect.

Clear lines of responsibility and command must be defined before an external contractor is called in to an existing work site.

None of the forest workers was wearing an avalanche transceiver. Workers must be provided with avalanche rescue beacons if they are exposed to a moderate level of risk, as discussed in Chapter 3, "Avalanche Risk Assessment."

Communications are all-important. The loggers were not on the same radio frequency as the avalanche technicians, forestry company office, or contractor, who was several kilometres away in a grader.

Development of Safe Work Procedures for Snow Stability Assessment in Active Harvest Areas

After the event, the avalanche technicians worked together with the WCB and the forestry company to establish safe work procedures, a summary of which follows:

Rationale and Recommendations

Snow avalanches may pose a threat to logging crews working in active and inactive timber harvest areas in steep snow-covered terrain throughout the winter and spring. Avalanche likelihood is related to snow stability and the presence of a trigger. Snowpack observations enable

snow stability to be assessed so that safe risk management decisions can be made.

It is strongly recommended that logging crews be adequately trained and supplied with appropriate safety equipment when working in potential avalanche terrain. Training should include an annual one-day avalanche course that addresses specific issues encountered by loggers in avalanche-prone terrain. Personal protective equipment should include avalanche transceivers for everyone onsite and easily accessible rescue caches containing avalanche probes and shovels positioned outside the avalanche-prone area.

The following summary of safe work procedures is intended to minimize the exposure of logging crews and related workers to avalanches while snow stability is being assessed.

Safe Work Procedures

Snow stability assessment must be undertaken by a minimum of two people, one of whom will have a CAA Level 2 qualification and avalanche forecasting experience. Both of these people will be equipped with, and competent in the use of, avalanche transceivers and standard rescue equipment (probes and shovels). The assessment team will have a minimum of two radios capable of communication with workers and equipment in the vicinity.

Depending on the local terrain within the harvest and work area, workers, other than those on the assessment team, may be restricted to a "safe area" not potentially exposed to any avalanche that may initiate in the area being assessed. These "safe areas" will be determined by the avalanche technician in charge and communicated to the logging foreperson.

The possibility that traditional "presumed areas of safety" may no longer offer protection from avalanches if the upslope forest cover has changed must be factored into decisions. Depending on the size of the logged opening and the terrain configuration, snow avalanches may occur in areas where none have occurred before. Avalanche tracks and runout zones may yet be created or extended. This must be considered when safe areas are being defined.

When possible, snow observations will be scheduled on days when no logging crews are working in the vicinity of the area being assessed. If such scheduling is not feasible, the logging crew will be required to allow

the snow observation crew adequate time to gather the information necessary to make the snow stability assessment. During this time, workers will be required to vacate the vicinity of the area of potential hazard as determined by the avalanche technician. This restriction will be cancelled if the avalanche technician determines the risk of avalanche initiation to be low.

In an active harvest area, there may be anomalies in the snowpack structure when it is compared with surrounding undisturbed snow. This possibility will be investigated and considered as a part of the snow stability assessment.

Upon the completion of the fieldwork, but before departure from the potential hazard area, the assessment team will contact the client (forest licensee) and the logging contractor (if onsite) and supply an interim stability assessment. A full report, including plotted snow profiles, snow stability assessment, and recommendations, will then be submitted to the client.

(Source: Workers' Compensation Board [WCB], current as of March 2000, subject to periodic review)

Snow avalanches can constitute a workplace hazard if logging or other operations are undertaken on or below steep terrain where an unstable snowpack creates avalanche danger in winter or spring.

The *Workers' Compensation (Occupational Health and Safety) Amendment Act 1998* came into force on October 1, 1999. Section 115 sets out general duties of employers as follows:

***Section 115** (1) of the Act requires that every employer must:*

(a) ensure the health and safety of

(i) all workers working for that employer, and

(ii) any other workers present at a workplace at which that employer's work is being carried out, and

(b) comply with this Part, the regulations and any applicable orders.

(2) Without limiting subsection (1), an employer must:

(a) remedy any workplace conditions that are hazardous to the health or safety of the employer's workers,

(b) ensure that the employer's workers

(i) are made aware of all known or reasonably foreseeable health or safety hazards to which they are likely to be exposed by their work,

(ii) comply with this Part, the regulations and any applicable orders, and

(iii) are made aware of their rights and duties under this Part and the regulations,

(c) establish occupational health and safety policies and programs in accordance with the regulations,

(d) provide and maintain in good condition protective equipment, devices and clothing as required by regulation and ensure that these are used by the employer's workers,

(e) provide to the employer's workers the information, instruction, training and supervision necessary to ensure the health and safety of those workers in carrying out their work and to ensure the health and safety of other workers at the workplace.

***Section 119** requires that every owner of a workplace must:*

(b) give to the employer or prime contractor at the workplace the information known to the owner that is necessary to identify and eliminate or control hazards to the health or safety of persons at the workplace.

Blasting Operations

Part 21.85 of the Occupational Health and Safety Regulations (B.C. Regulation 296/97) **relates to blasting operations used in snow avalanche control.**

21.85 ***Snow Avalanche Control***

(1) Explosive charges must not be dropped from a helicopter or other aircraft, placed manually on site by workers, or projected by any means for the purpose of avalanche control, until the proposed work procedures have been submitted to and accepted by the board.

(2) Explosives must not be primed until the last most practicable moment, which means that point in time when the explosives are as close to the control route as possible, in a safe, sheltered location excluded from public access.

(3) The pull-wire lighter must not be placed on the safety fuse assembly until immediately before placing the charge.

(4) The employer must ensure that procedures are reviewed annually and that proposed changes to the procedures are submitted to the board for approval before implementation.

The Canadian Avalanche Association has consulted with the WCB to establish safe work procedures for the priming of explosives at "the last most practicable moment." Consultation on other matters is ongoing.

Forestry Operations

Part 26.17 of the Occupational Health and Safety Regulations (B.C. Regulation 296/97) **relates specifically to weather conditions as they may affect snow avalanches while 26.18 relates to landslides and/or snow avalanches in forestry operations.**

26.17 ***Weather Conditions***

When weather conditions create hazards to workers, additional precautions must be taken as necessary for the safe conduct of the work.

26.18 ***Landslides/Avalanches***

In a forestry operation where there may be a risk of a landslide or avalanche,

(a) the risk must be assessed in accordance with a standard acceptable to the board,

(b) if a risk is found to be present, written safe work procedures must be developed meeting the requirements of the standard, and

(c) workers must be educated in the safe work procedures.

APPENDIX 2 SAFE FOREST OPERATIONS IN AVALANCHE-PRONE TERRAIN

A 2.1 Safe Work Procedures

(Adapted from B.C. Ministry of Transportation's Snow Avalanche Program)

The following example is intended to serve as a template for safe work procedures. It should be adapted to suit the scale of operation and degree of hazard encountered in an area.

This management system assumes that:

a) *there will be one person responsible for avalanche hazard management.* That officer will have specialist training in snow stability evaluation (i.e., CAA Level 2). The snow stability will be rated on a scale from Very Good to Very Poor (see Appendix 6). That person will make a daily formal assessment of the avalanche danger in winter (Low, Moderate, or High) for various elevations and aspects.

b) *a written avalanche search and rescue plan exists.*

c) *all potential avalanche paths are identified and mapped in an avalanche atlas, and an overall risk rating is produced for the operating areas (Low, Moderate, High, or Very High).* See Section 3.2, "Avalanche Risk Classification," and Table 12.

d) *signage is in place at all ploughed major forest roads intersected by avalanches.*

e) *all proposed cutblocks are rated for avalanche initiation or runout.*

Field personnel must:

a) be able to recognize avalanche terrain and the safe areas within the operating area;

b) understand the importance of having warm clothing available inside machinery in case of burial;

c) know the correct procedures to follow when buried by an avalanche, whether inside or outside a vehicle or machinery;

d) know the correct procedures to follow when an avalanche is on a forest road;

e) know where all other personnel working in an avalanche area are during hazardous periods;

f) know the correct procedures to follow regarding the use of heavy equipment in avalanche areas;

g) know the basic indicators of changes in snowpack stability and the need to report them to an officer for avalanche risk management; and

h) know the location of rescue caches and have access to emergency avalanche transceivers, probes, radios, and first aid kits.

Rescue Procedures

All field personnel must know the procedures for:

a) reporting the accident
b) locating and using rescue equipment
c) using avalanche rescue beacons
d) using the *Avalanche Search and Rescue Plan*, including:
   - initiating the rescue operation
   - following the line of command for rescue
e) carrying out an avalanche rescue.

Avalanche Awareness and Safety Training

Snow avalanche paths that affect operating areas throughout the forest should be identified on waterproofed maps and orthophotos. Workers operating in these areas require a specific level of avalanche safety training that depends on:

a) the severity of avalanche terrain and frequency and magnitude of avalanches expected in the area (risk);
b) the location of the area (i.e., if the area is remote and/or radio communications are poor, then more extensive training is required);
c) the position of the person and his or her possible involvement in an avalanche rescue; and
d) the regularity with which staff are expected to work in the area (i.e., road maintenance or logging personnel working in moderate or high-hazard areas will require a higher level of training than personnel working in low-hazard areas on an irregular basis).

Assessment of Avalanche Danger

At the beginning of winter, the officer responsible for avalanche risk management will begin monitoring the snowpack to establish when avalanche thresholds are attained (largely a function of surface roughness). Thereafter, the avalanche danger, as assessed at each work site, will be broadcast by radio to all workers at the start of each working week, and written notice provided to all contractors. Contractors will advise all workers of the avalanche danger and modify work procedures accordingly. The officer will be advised of rate of harvest at various operations. New clearcuts above roads may create potential paths that did not exist at the start of the winter.

Assessments are to be updated each working day if conditions change or are expected to change.

Low Avalanche Danger

During periods of low danger, workers and contractors may proceed with normal forest operations. The officer responsible for avalanche risk management will:

a) Ensure that avalanche rescue equipment is maintained and ready for use.

b) Ensure that turnarounds on forest roads are free of snow. Pullouts in designated avalanche areas must not be cleared of snow once avalanche thresholds are attained.

c) Ensure that correct avalanche safety measures are practised. This includes not stopping, re-fuelling, or parking vehicles and equipment in designated avalanche areas on forest roads.

d) Monitor and record changes in:
   - avalanche occurrence observations
   - basic indicators of snowpack stability
   - current weather observations.

   Functions outlined in d) may be delegated to a contractor or other worker, provided the information is transmitted by radio in a timely manner.

Moderate Avalanche Danger

During periods of moderate danger, all workers and contractors will:

a) Maintain communication with the officer responsible for avalanche risk management and immediately give notice of any apparent changes in the snow avalanche danger.

b) Immediately notify the officer responsible for avalanche risk management if avalanche activity is increasing or affecting any forest road or harvest area.

c) If working outside of vehicles or machines in potential avalanche areas, move to safe areas when instructed.

d) Monitor and report to the officer responsible for avalanche risk management on:
   - avalanche occurrences
   - basic indicators of snowpack stability
   - current weather.

e) Take additional observations if requested by the officer responsible for avalanche risk management.

f) Call by radio upon entering and leaving avalanche areas and when travelling through signed avalanche paths on forest roads.

g) Ensure that equipment and resources are available for working in pairs, should the avalanche danger warrant. Working in tandem shall

occur at the discretion of the officer responsible for avalanche risk management.

h) Not operate stationary equipment (e.g., yarders) within potential avalanche areas unless the officer responsible for avalanche risk management has been consulted and given approval. If stationary equipment is allowed in the avalanche area, an off-site spotter may be required. Machines can work in separate, but adjacent, areas if the operators have visual contact, thus eliminating the need for a spotter.
i) Ensure that one person regularly monitors the location of road maintenance staff such as grader operators. All persons working alone shall check in at 30-minute intervals.
j) Monitor weather forecasts and avalanche bulletins.
k) Conduct road closures to allow for avalanche control (helibombing) programs as directed by the officer responsible for avalanche risk management.

High Avalanche Danger

During periods of high danger, the officer responsible for avalanche risk management will:

a) Advise the contractor to close work sites in potential avalanche areas that may be affected by snow avalanches.
b) Ensure that there is no travel by any personnel in or through avalanche areas except where personnel are needed to carry out:
   - a post-closure sweep of the area
   - avalanche and weather observations
   - avalanche control operations
   - any other task as approved by the officer responsible for avalanche risk management.
c) Ensure that no travel or work occurs at night in the avalanche area.
d) Ensure that correct avalanche safety procedures are practised.
e) Ensure that no other regular forest and harvest activities are conducted inside the affected avalanche area.

During periods of high danger, contractors and workers operating outside of potential avalanche areas will:

a) Monitor and report to the officer responsible for avalanche risk management:
   - avalanche occurrences
   - basic indicators of snowpack stability
   - current weather.
b) Take additional observations as necessary or as requested by the officer responsible for avalanche risk management.

c) Monitor weather forecasts and avalanche bulletins.
d) Continue forest road maintenance as required within safe areas, in consultation with the officer responsible for avalanche risk management. Machine operators must work in tandem in potential avalanche areas and schedule radio checks at 15-minute intervals.

A 2.2 Response – Avalanche on Road

(Adapted from Crestbook Forest Industries)

A card with the following information is to be carried in all vehicles (the card should be plastic laminated to a forest road map).

If you encounter an avalanche on a road:
a) Stay in the vehicle.
b) Radio the supervisor or area office (or whomever you can contact if the former are not accessible) and specify the location and avalanche size (kilometre point on road, length of road covered, and maximum depth on road).
c) Try to determine if anyone might be caught. (Is the avalanche large enough? Is anyone missing?)

If someone might be caught, then initiate a rescue immediately:
a) Evaluate the upslope danger. (Do multiple start zones exist? Could more avalanches occur?) Do not proceed into the path if you are alone and if the avalanche danger persists.
b) Determine an escape route. Appoint a spotter if possible. Expose only a minimum number of people to potential hazards.
c) Ensure that your avalanche transceiver is on. Take a portable radio with you. If that is not possible, tell someone that you are going onto the deposit and that you will call back in 5 minutes.
d) Conduct a quick search of the entire deposit, looking for visual clues, and check for an avalanche transceiver signal. If no signal is apparent, probe the likely burial spots.

If you are certain that nobody is caught:
a) Do not venture onto the deposit.
b) Move to a safe location, notify the officer responsible for avalanche risk management, and await instructions.

If your vehicle gets caught in an avalanche or stuck in avalanche debris:
a) Stay in the vehicle.

b) Shut off the engine and lights (to avoid the risk of carbon monoxide poisoning and to conserve the battery) and do not smoke.
c) Radio the supervisor or area office (or whomever you can contact if the former are not accessible). Describe the location and size of the avalanche (give the road kilometre point, length of road covered, and maximum depth on road). Leave the radio on.
d) Try to determine if anyone else might be caught and radio out this information.
e) Ensure that your avalanche transceiver is in "transmit" mode.
f) Only if you are certain that no further danger exists and that you can move to a safe location should you leave the vehicle.
g) If the vehicle is buried, push a probe out through the window and up to estimate the depth of burial. Leave the probe in place to mark your position for the rescue party and to provide an air path.
h) Do not start the vehicle. Put on extra clothes for warmth.

A 2.3 Avalanche Search and Rescue Plan – Office Procedures

(Adapted from Crestbook Forest Industries)

The following summarizes the key elements of an avalanche rescue plan for office staff who will need to co-ordinate the rescue effort. The plan should be modified to suit the local operating environment. See Chapter 8 of the Avalanche Handbook *(McClung and Schaerer 1993) and* Backcountry Avalanche Awareness *(Jamieson 1997) for further information.*

Time is of the essence. Keep a log of persons and agencies that have been contacted, noting arrangements, estimated times of arrival, etc. The office must function as a central dispatch and rescue co-ordination centre. Having two or more people share the contacting duties will speed the rescue effort. Appoint a person who is not involved in the rescue to deal with inquiries from the media.

1. **Dispatch the first rescue party to the site** with basic rescue equipment. Obtain probes and shovels from caches on the way to the site (refer to the emergency caches map).
2. **Contact Search and Rescue** (SAR) or nearest **Canadian avalanche rescue dog handler** (CARDA). Use whoever can most quickly access the site by helicopter (see dog team list below). **Arrange a helicopter pick-up location with the dog master.** If leaving the message on a pager, report the incident, give a contact phone number and explain that helicopter transport is being arranged and you will call back with the pick-up location. Even after leaving a pager message, contact a second or third dog team and make transport arrangements. If

weather may prevent helicopter access to the site, arrange to **fly in as far as possible** and arrange for vehicle pick-up and transport from there.

3. **Establish communication with field rescue leader,** specify the channel to use, and attempt to clear other radio users. Note the Frequency in use _____, or the Channel _____.
4. If no member of the team is trained in avalanche rescue, assign one person to advise the most suitable team member on the procedures that a field rescue leader should follow. Have a staff member with snow safety training use the manual's *Avalanche Response, Probe Searches,* and *Transceiver Search* sections to talk the rescue team through the basics.
5. Determine a location suitable for **landing a helicopter** with field personnel. Be prepared to give an accurate description of the location and landing site to the pilot; obtain GPS co-ordinates if the pilot is coming from out of the area.
6. Determine the location of a suitable site for ground crew access (e.g., kilometre point on the road, other directions to site).
7. **Contact a helicopter to transport the dog team** to the site. (See helicopter list below.)
8. Contact the Provincial Emergency Program at 1-800-663-3456.
9. Contact the local RCMP detachment (see RCMP list attached). Have them send an ambulance.
10. Contact _____ or _____ at head office (local _____).
11. Contact the forest officer responsible for avalanche risk management (local _____ at head office or _____ [home]).
12. Stop all logging-related traffic on the roads as soon as possible. Send some pilot vehicles out to the road head to lead rescuers arriving by road to the accident site.

Contact numbers:

RCMP

SAR / CARDA dog teams

Helicopter pilots

Heliski companies

Note: Heliski companies may be able to bring trained rescue personnel to some sites quickly.

(Procedures updated and contact numbers checked: ____/____/ 20____)

A 2.4 Avalanche Rescue Equipment

(Adapted from B.C. Ministry of Transportation Snow Avalanche Programs)

FIRST PARTY Rescue Pack	
	Rescue pack labelled FIRST PARTY with tag listing the following contents:
1	Rescue plan (applicable section) and pencil
4	Collapsible probes
2	Shovels with short "D" handles
30	Marking wands with bright red, blue, and orange flagging
1 (roll)	Flagging tape
1	WCB basic first aid kit in weatherproof case
2	Heat packs
1	Blankets – disposable
1	Blankets – space, re-usable
1	"Fox 40" rescue whistle or air warning horn
4	Headlamps with new batteries each winter (remove batteries each spring)
1	Hand lantern with new batteries each winter (remove batteries each spring)
1	Flagging vest, labelled "Avalanche Rescue"
5	"Cyalume" light sticks or similar

Rescue equipment must be maintained in good order and be ready to go at all times.

Rescuers should also have ready access to one or more portable radios.

One first party pack must be kept in the Emergency Transport Vehicle (ETV).

One pack must be available at a designated permanent rescue cache and ready to be transported by helicopter.

SECOND RESCUE PARTY Equipment	
Pack labelled SECOND PARTY with tag listing the following contents:	
20	One-piece probes
10	Shovels with short "D" handles
150	Marking wands with bright red, blue, and orange flagging
1	WCB Level 1 first aid kit
10	Heat packs
2	Blankets – disposable
2	Blankets – space, re-usable
4	Rope (30 m lengths of 12 mm diameter)
1	Loud hailer
1	"Fox 40" rescue whistle or air warning horn
6 (pair)	Snowshoes
10	Headlamps with new batteries each winter (remove batteries each spring)
5	Hand lantern with new batteries each winter (remove batteries each spring)
1	Toboggan kit, with back board and cervical collar
1	Portable lighting and generator (need not be part of kit but location documented)
1	Oxygen set

Second party equipment should be stored at a designated rescue cache (e.g., on a forest mainline road or at camp) and be readily transportable by helicopter.

APPENDIX 3 ONLINE RESOURCES AND INFORMATION SOURCES

Internet URLs (world wide web sites) current as of December 2002. (Links are indicated by blue text.)

Canadian Sites

Canadian Avalanche Association
www.avalanche.ca
Site offers an assessment of current avalanche conditions in western Canada. Information is drawn from an extensive reporting network. Intended for recreationists. Limited prediction. The CAA issues avalanche bulletins for the North Columbia Mountains, South Columbia Mountains, South Coast Mountains, and the Canadian Rockies. An example is given on pages 156–157. Recordings of the bulletins are available at 1-800-667-1105.

UBC Avalanche Group
www.geog.ubc.ca/avalanche
Includes FRBC-funded research outputs.

University of Calgary Applied Snow and Avalanche Research Group
www.eng.ucalgary.ca/Civil/Avalanche/

Division of Engineers and Geoscientists in the Forest Sector
www.degifs.com
Includes a skill set for qualified registered professionals undertaking snow avalanche assessments.

Provincial Emergency Program
www.pep.bc.ca

Canadian Avalanche Rescue Dog Association
www.carda.bc.ca

Precipitation and snow accumulation data–British Columbia
www.weatheroffice.ec.gc.ca/forecast/Maps/bc_e.html or
www.msc-smc.ec.gc.ca/climate/index_e.cfm or
srmwww.gov.bc.ca/aib/wat/rfc/archive/index.html or
eww.bchydro.bc.ca/info/res_hydromet/res_hydromet825.html

United States Sites

West Wide Avalanche Network, Colorado
www.avalanche.org

An online library of selected papers from the biannual International Snow Science Workshops.
www.avalanche.org/~moonstone

North West Avalanche Centre
www.nwac.noaa.gov
Mountain meteorologists provide avalanche forecasts for Northern Cascades. Includes hourly weather data from Mt. Baker and other sites.

Idaho Panhandle Nation Forest
www.fs.fed.us/ipnf/visit/conditions/backcountry/index.html

North West Montana Glacier Country Avalanche Centre
www.glacieravalanche.org

An informal online discussion group that operates under the banner of the Cyberspace Avalanche Centre (CSAC). The site provides an open forum for discussion.
www.csac.org/Canada

Other Sites

International Snow Science Workshop (ISSW)
www.issworkshop.org

Swiss Federal Research Institute (SLF; English)
www.wsl.ch/welcome-en.ehtml

Link to proceedings of International Union of Forest Research Organisations (IUFRO) workshops on mountain forests.
www.wsl.ch/forest/waldman/mfe/welcome-en.ehtml

PC *software used to plot and store snow profile records,* initially developed by the B.C. Ministry of Transportation's Snow Avalanche Program, is marketed by Gasman Industries of Victoria, B.C. as "SnowPro."
www.gasman.com

Example of a Canadian Avalanche Association Public Bulletin

South Columbia Mountains February 8, 2001
NOT!CE OF UNUSUAL AVALANCHE CONDITIONS: Valid until further notice.

This season, avalanche professionals between the Inner Coast Mountains and the Rocky Mountains have observed snowpacks that are unusually weak. The combination of below-normal snow depth and low temperatures has produced layers of faceted grains and surface hoar with a low strength. These types of weak layers can persist for a long time, and the avalanche danger will increase with every load of new snow onto this weak base. The present snowpack is less stable than in most other years and remarkably different from the snowpack at the same time last winter. Backcountry users will have to pay much attention to snowpack structure and strength during this winter.

WEATHER: Last weekend's storm cycle ended on Monday and was followed by a shift to northerly winds and a significant drop in temperature. Northern parts of this region reached -25°C, while the Kootenays dropped to -15. Look for a slight moderation of temperatures into this weekend, and light snowfall amounts giving minor accumulations.

SNOWPACK: 60–80 cm of last week's storm snow sits on a buried layer of surface hoar and suncrust in some locations. Along with another new snow instability down about 30 cm from the top, surface slabs are a significant concern and can be triggered easily on these layers. Primary concern remains with the weak facets and depth hoar near the base of the snowpack. This layer has shown little improvement and is still incredibly weak. Combined with a near-critical load above it, the potential for large, destructive avalanches is quite real.

AVALANCHES: Numerous avalanches were triggered by humans and explosives all week. Often the triggers were from a long distance away from where the actual avalanche happened. In one case a skier triggered a Size 3.5 avalanche from a slope nearby. **Several avalanches in clearcuts were also noted.** Many observers are reporting avalanches occurring on slopes that released earlier in the season but have now become reloaded.

(continued)

Forecast Of Avalanche Danger Up To Monday Evening (Feb 12)

Alpine – Considerable
Treeline – Considerable
Below Treeline – Moderate

TRAVEL ADVISORY: Avalanche conditions in this region are extremely touchy right now. Backcountry ski guides across the area are nervous and on their toes constantly. Conditions like this are complicated and very difficult to predict. Safe route finding and good terrain skills are essential components of travelling safely through the backcountry right now.

APPENDIX 4 AVALANCHE SITE IDENTIFICATION FORM

Observer _____ Site _____ Date _____ Weather _____

1. Field Evidence of Avalanche Activity Enter: ✓ Yes × No ? Unknown

		Start Zone	Track	Runout Zone
A	**Normal erect vegetation for site is**			
A1	Missing			
A2	Unusually sparse and scattered			
A3	Replaced by other species			
A4	Broken off near ground			
A5	Pushed over but not broken			
B	**Damage to standing trees and brush**			
B1	Entire plant bent or deformed			
B2	Tops broken out			
B3	Limbs, twigs, or needles missing			
B4	Trunks or tree limbs scarred			
C	**Debris and Colluvium**			
C1	Snow abnormally deep or persistent			
C2	Tree trunks, limbs in debris			
C3	Branches, needles, brush			
C4	Colluvium as cones or mounds, etc. *			
C5	Other debris (specify)			

** Not due to glacial or fluvial processes.*
(After Martinelli 1975)

2. Surface Cover (percent of total area in each component of the avalanche path)

	Start Zone	Track	Runout Zone
Dense timber			
Scattered timber			
Brush above 2 m			
Brush under 2 m			
Grass and shrubs			
Bare ground			
Large blocks and boulders >1 m in height			
Blocks and boulders >256 mm diameter (b axis)			
Rubble 2–256 mm diameter (b axis)			
Bedrock (relatively smooth)			
Other (specify)			
	100 %	100 %	100 %

3. Detailed Site Investigation (features often not mapped at 1:20 000 scale)

Locate features on an orthophoto or oblique air photo.

Enter: ✓ Yes ✕ No ? Unknown

Feature	✓ ✕ ?	Map location	Comment if present
Convex terrain in starting points			
Cliffs in start zone			
Gully headwalls in start zone			
Timber in start zone			
Multiple tracks			
Cliff band in track(s)			
Benches in track(s)			
Channelized track(s)			
Sinuous track(s)			
Potential for avalanche to leave track			
Snow roll in start zone			
Cornice			
Elements at risk in or near track			
Elements at risk in or near runout zone			

Note: Colour photographs and photo-documentation should be provided where appropriate.

4. Snow and Weather Data

Nearest weather station _____ (Elev. ____ m, Year's record _____)
Nearest snow course _____ (Elev. ____ m, Year's record _____)
Direction from which most snow drifting occurs _____
Snow depths expected (30-year average) _____ cm and water equivalent _____ mm

5. Verbal or Written Accounts of Avalanche Activity

Avalanche runout reaches	Frequency	Information Source	Information Reliability	Comment
Lower end of track				
End of current runout zone				

6. Specific Avalanche Events

Date	Runout reached	Damage or Injury	Information Source	Information Reliability	Comment
1.					
2.					
3.					
4.					

APPENDIX 5 AVALANCHE ASSESSMENT CHECKLIST

Potential for avalanche initiation within cutblock (Type 1 avalanche)

Guidance: Refer to Figures 23 and 24 and Tables 11–13

Observer _____ Site _____ Date _____ Weather _____

Evaluation Factor	Observations / Data	Contribution to Avalanche Risk		
		Likely	Possible	Unlikely
Incline in harvest area				
Incline below harvest area				
Surface roughness				
30 year snow supply				
Threshold snow supply				
Snow climate				
Wind				
Remaining vegetation				
Cross-slope shape				
Down-slope shape				
Terrain features				
Potential start zone area				
Avalanche obs. (relevant)				
Aspect				
Conclusion				

Checklist from Canadian Avalanche Association/FCSN Forestry Risk Mapping course material, 2002 (methodology under development).

Potential for extension of avalanche runout into cutblock (Type II avalanche)

Guidance: Refer to Figures 23 and 24 and Tables 11 and 12

Observer _____ Site _____ Date _____ Weather _____

Evaluation Factor	Observations / Data			
Start zone incline				
Wind				
Start zone feature				
Aspect				
Start zone area				
Track incline above harvest				
Track configuration				
Path width				
30 year snow supply				
Threshold snow supply				
Snow climate				
History				
Frequency/Magnitude				
	Contribution to **Increased** Avalanche Risk ☑			
		Likely	Possible	Unlikely
Harvest area incline				
Down-slope shape				
Cross-slope shape				
Surficial materials				
Terrain features below				
Incline below				
Conclusion				

Checklist from Canadian Avalanche Association/FCSN Forestry Risk Mapping course material, 2002 (methodology under development).

APPENDIX 6 SNOW STABILITY RATING SYSTEM

Code	Term	Definition
VG	Very Good	Very large triggers, such as cornice falls or explosives, produce only sluffs. Stability tests generally produce little or no results.
G	Good	Natural avalanches are not expected. Avalanches may be triggered by heavy loads in isolated terrain features. Stability tests generally produce moderate to hard results.
F	Fair	Natural avalanches can be expected in isolated terrain features. Avalanches may be triggered by light loads in areas that have specific terrain features or certain snowpack characteristics. Stability tests generally produce easy to moderate results.
P	Poor	Natural avalanches can be expected in areas with terrain that has specific features or certain snowpack characteristics. Stability tests generally produce easy results.
VP	Very Poor	Natural avalanches can be expected on a widespread basis. Stability tests generally produce very easy to easy results.
U	Unknown	

(CAA 1995, revised 1996)

Definitions:

Heavy load: a snowmobile or explosives
Light load: one person on snowshoes, skis, or foot
Isolated terrain features: extremely steep terrain, steep convex rolls
Specific terrain features: lee slopes, sun-exposed aspects
Certain snowpack characteristics: shallow-faceted grains, persistent weaknesses

When applying the snow stability rating system:

- specify the stability for three elevation bands: alpine, timberline, below timberline
- give the expected stability trend for the next 12–24 hours (when possible)
- use the following terms: improving, steady, decreasing
- specify a confidence level in the ratings when appropriate

Experienced observers may qualify the rating based on:

- topography (aspect, slope, elevation)
- spatial extent (localized or widespread)
- time of day
- level of the unstable layer in the snowpack (e.g., near surface, mid level, deep)

See Appendix F of the *Avalanche Handbook* (McClung and Schaerer 1993) for a discussion of the merits of this and other snow stability and hazard rating systems.

GLOSSARY

(After B. Jamieson. A more comprehensive illustrated glossary is available at the CAA web site.)

Avalanche transceiver An electronic device worn by people in avalanche terrain. In "transmit mode," it constantly transmits a radio signal that becomes stronger at close range. If someone with a transmitting transceiver is buried, the other members of the group can switch their transceivers into "receive" mode and follow a search pattern that locates the strongest signal. Probing and shovelling are then used to find the victim.

Bed surface The surface on which an avalanche runs. Not to be confused with failure plane.

Cornice An overhanging build-up of snow, usually on the lee side of a ridge.

Cross-loading Occurs when wind blows across a slope, picking up snow from the windward face and depositing it in the lee of convexities, surface depressions, and other terrain features.

Crust A hard, usually thin, snow layer, either one or a few grains in thickness, and consisting of uniform, well-bonded material.

Depth hoar An advanced, generally larger, form of faceted grain. Depth hoar grains are striated and, in later stages, often form hollow shapes. Cup-shaped grains are a common form of depth hoar. This type of grain can form at any level in the snowpack, but is most commonly found near the base of shallow snowpacks following periods of cold weather.

Facets (also called ***faceted grains***) A grain form that develops in response to a strong temperature gradient within the snowpack. Grains grow flat faces through a process known as "kinetic growth" or, simply, "faceting." Facets commonly form near the snow surface or where the snowpack is shallow during periods of cold clear weather (see also ***depth hoar***).

Failure plane The plane in a snowpack along which a fracture spreads, releasing a slab avalanche. The bed surface usually lies immediately below the failure plane.

Melt-freeze crust A layer of snow that has been warmed until liquid water forms between the grains and then refreezes to form a relatively strong layer. Crusts sometimes form the bed surface for avalanches.

Propagation The spreading of a fracture or crack. The shear fractures that spread along weak layers and release slab avalanches tend to propagate farther under thicker, harder slabs than under thinner, softer slabs.

Rime A deposit of ice from supercooled water droplets. Rime can accumulate on the windward side of rocks, trees, or structures or on falling crystals of snow. When snow crystals cannot be recognized because of rime, the grains are called "graupel."

Rounded grains (rounds) Under weak temperature gradients or uniform temperatures, branched and angular grains decompose into more rounded shapes called "rounds." This process occurs in dry snow and involves the sublimation of ice from convex parts of grains into hollows. Rounding also tends to build bonds between grains (a process termed "sintering"). Consequently, layers of rounded grains are often stronger than layers of faceted grains of similar density.

Slab One or more cohesive layers of snow that may start to slide together, creating a slab avalanche.

Sluff A small avalanche usually made up of loose snow.

Snowboard A solid, flat, white-painted square of plywood, approximately 600 × 600 mm square with a vertical rule projecting upward. Laid on the ground or on the snow surface, it is used by observers to measure the new snow depth and equivalent water content.

Stepped down A feature of a slab avalanche when the motion of the initial slab causes lower layers to slide, resulting in a second bed surface deeper in the snowpack. A step in the bed surface is usually visible.

Storm snow The snow that falls during a period of continuous or almost continuous snowfall. By definition, a storm terminates after a day when new snow accumulation is less than 1 cm.

Sun crust A term used to refer to a melt–freeze crust that is more noticeable on sunny slopes than on shady slopes. According to the International Classification for Seasonal Snow on the Ground (Colbeck et al. 1990), a sun crust (also called "firnspiegel") refers to

a thin transparent layer caused by partial melting and refreezing of the surface layer.

Surface hoar Crystals, often shaped like feathers, spikes, or wedges, that grow upward from the snow surface when air just above the snow surface is cooled to the dew point. This is the winter equivalent of dew. Surface hoar grows most often when the wind is calm or light on cold, relatively clear nights. These crystals can also grow during the day on shady slopes. Once buried, layers of surface hoar are slow to gain strength, sometimes persisting for a month or more as potential failure planes for slab avalanches.

Temperature gradient The change in temperature with depth in the snowpack. For example, if the temperature 20 cm below the surface is 3°C warmer than the surface, then the temperature gradient in the top 20 cm averages 1.5°C per 10 cm. Gradients greater than 1°C per 10 cm are often associated with faceting of grains and weakening of layers, whereas lower gradients are usually associated with rounding of grains and strengthening of layers. However, the transition between faceting and rounding also depends on factors other than the temperature gradient. (Note that even though the centimetre is not a standard SI unit, its convenience makes it the preferred unit of length in snow avalanche work.)

Terrain trap A terrain feature that worsens the consequences should a person get caught in an avalanche. For example, gullies and road cuts increase the odds of a deep burial; treed areas increase the odds of traumatic injuries.

Water equivalent The depth of water (in millimetres) obtained by melting a core of snow (or by other techniques).

Whumpf The sound of a fracture propagating along a weak layer within the snowpack. "Whumpfing" sounds are indicators of local instability. In terrain steep enough to avalanche, whumpfs often occur simultaneously with slab avalanche release.

Wind-loaded Terrain on which the wind has deposited additional snow. Slopes on the lee sides of ridges are often wind-loaded.

Wind-slab One or more stiff layers of wind-deposited snow. Wind slabs usually consist of snow crystals broken into small particles by the wind and packed together.

REFERENCES

Berger, F. and E. Mermin. 1999. Modelling of forest cover influence on snow distribution to estimate the size of regeneration gaps that will not bring about the releasing of avalanches in Norway spruce stands. *In* Proc. IUFRO Workshop. Structure of mountain forests: assessment, impacts, management, modelling. Swiss Federal Institute for Forest, Snow and Landscape Research, Davos, Switzerland.

Blaschke, R. 1999. Monitoring of protection forests with GIS and high resolution satellite data. Possibilities of a wide ranged analysis as an instrument for the reconstruction planning in protection forests. *In* Proc. IUFRO Workshop. Structure of mountain forests: assessment, impacts, management, modelling. Swiss Federal Institute for Forest, Snow and Landscape Research, Davos, Switzerland.

Bolognesi, R., O. Buser, and W. Good. 1992. Local avalanche forecasting in Switzerland. *In* Proc. ISSW '92, International Snow Science Workshop, Breckenridge, Colo., pp. 11–14.

Borrel, G. 1992. The new French avalanche map. *In* Proc. ISSW '92, International Snow Science Workshop, Breckenridge, Colo., pp. 225–228.

Boucher, D., B. Hétu, and L. Filion. 1999. Late-Holocene development of a snow avalanche path in Mount Hog's Back, Gaspé Peninsula, Quebéc. *In* Proc. CANQUA-CGRC Annual Meeting, Univ. Calgary, Calgary, Alta.

Boyer, D.C. and P. Jordan. 2001. November 1999 fall storm: Kootenay Region. *In* Proc. Changing water environments: research and practice. Proc. Can. Water Resource Assoc. B.C. Branch, Whistler, B.C., pp. 24–33.

British Columbia Ministry of Environment, Lands and Parks. 1999. Biological and conservation data system. B.C. Conservation Data Centre, Victoria, B.C.

British Columbia Ministry of Forests. 1993. Engineering Manual. Engineering Section, Victoria, B.C.

_____. 1997. TIPSY: table interpolation program for stand yields [Software]. Research Branch, Forest Productivity and Decision Support Section, Victoria, B.C.

_____. 1999. Mapping and assessing terrain stability guidebook. Forest Practices Code of British Columbia. 2nd ed. Co-published by B.C. Min. For. and B.C. Min. Environ., Victoria, B.C.

_____. 2002. Forest road engineering guidebook. For. Prac. Br., Victoria, B.C. Forest Practices Code of British Columbia guidebook.

_____. 2002. Fish-stream crossing guidebook. For. Prac. Br., Victoria, B.C. Forest Practices Code of British Columbia guidebook.

British Columbia Ministry of Transportation and Highways. 1991. Terrace avalanche atlas. Snow Avalanche Program, Victoria, B.C.

_____. 1992. Ministry of Transportation and Highways - Ministry of Forests protocol agreement on controlling the impact of logging on the snow avalanche hazard to B.C. Highways. Victoria, B.C. Updated March 2002.

Burrows, C.J. and V.L. Burrows. 1976. Procedures for the study of snow avalanche chronology using growth layers of woody plants. Institute of Arctic and Alpine Research, Univ. Colo., Boulder, Colo. INSTAAR Occas. Pap. No. 23.

Butler, D.R. and G.P. Malanson. 1990. Non-equilibrium geomorphic processes and patterns on avalanche paths in the northern Rocky Mountains, U.S.A. J. Glaciol. 34(3):257–270.

Canadian Avalanche Association (CAA). 2002. Observation guidelines and recording standards for weather, snowpack and avalanches. P.L. Weir (editor). Revelstoke, B.C.

_____. 2002. Land managers guide to snow avalanche hazards in Canada. Revelstoke, B.C., National Search and Rescue Secretariat, Ottawa, Ont.

Canadian Standards Association (CSA). 1997. Risk management: guidelines for decision makers. Etobicoke, Ont. CAN/CSA-Q850-97.

Cave, P. 1992. Hazard acceptability thresholds for development approvals by local government. *In* Proc. Geologic Hazards in British Columbia. Victoria, B.C. Geologic Hazards '91 workshop, B.C. Geol. Surv. Branch Open File 1992–15.

Chilton, R.H.H. 1981. A summary of climate regimes of British Columbia. B.C. Min. Environ., Assessment and Planning Div., Victoria, B.C.

Clarke, J. and D. McClung. 1999. Full depth avalanche occurrences caused by snow gliding, Coquihalla, British Columbia, Canada. J. Glaciol. 45(151):539–546.

Claus, B.R., S.O. Russell, and P.A. Schaerer. 1984. Variation of ground snow loads with elevation in Southern British Columbia. Can. J. Civil Eng. 11:480–493.

Colbeck, S.C. 1997. A review of sintering in seasonal snow. U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, N.H. CRREL Report 97–10.

Colbeck, S., E. Akitaya, R. Armstrong, H. Gubler, J. Lafeuille, K. Lied, D. McClung, and E. Morris. 1990. The international classification for seasonal snow on the ground. International Commission on Snow and Ice of the International Association of Scientific Hydrology. Co-Issued by the International Glaciological Society. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, N.H.

Conway, H., W. Carran, and A. Carran. 2000. The timing, size and impact of avalanches on the Milford Highway, New Zealand. *In* Proc. ISSW 2000, International Snow Science Workshop, Big Sky, Mont., pp. 167–172.

Conway, H. and C.F. Raymond. 1993. Snow stability during rain. J. Glaciol. 39(133):635–642.

Conway, H. and C. Wilbour. 1999. Evolution of snow stability during storms. Cold Reg. Sci. Technol. 30:67–77.

Cupp, D. 1982. Avalanche! Battling the juggernaut. National Geographic 162(3):290–305.

Davis, R., B. Jamieson, J. Hughes, and C. Johnston. 1997. Observations on buried surface hoar: persistent failure planes for slab avalanches in British Columbia, Canada. *In* Proc. ISSW '96, International Snow Science Workshop, Banff, Alta., pp. 81–85.

de Scally, F. 1992. Influence of avalanche snow on snowmelt runoff. J. Hydrol. 137:73–97.

_____. 1996. Hydrologic role of snow avalanches in high mountain environments: a review. *In* Proc. 64th Western Snow Conf., Bend, Oreg., pp. 69–80.

Dufour, F., U. Gruber, P. Bartelt, and W.J. Ammann. 2000. Overview of the 1999 measurements at the SLF test site, Vallee de la Sionne. *In* Proc. ISSW 2000, International Snow Science Workshop, Big Sky, Mont., pp. 527–534.

Edwards, A.W.F. 1992. Likelihood. Expanded ed., Johns Hopkins Press, Baltimore, Md. and London, U.K.

Einstein, H.H. 1997. Landslide risk: systematic approaches to assessment and management. *In* Proc. Workshop on Landslide Risk Assessment, Honolulu, Hawaii. D.M. Cruden and R. Fell (editors). A.A. Balkema, Rotterdam, Netherlands, pp. 25–50.

Elms, D.G. 1998. Risk management: general issues. *In* Owning the future: integrated risk management in practice. Centre for Advanced Engineering. Wellington, N.Z., pp. 43–62.

Environment Canada. 1996. Meteorology for snow avalanche professionals: from theory to practice. Mountain Weather Service, Kelowna, B.C.

Fell, R. 1994. Landslide risk assessment and acceptable risk. Can. Geotech. J. 30:261–272.

Fell, R. and D. Hartford. 1997. Landslide risk management. *In* Proc. Workshop on Landslide Risk Assessment, Honolulu, Hawaii. D.M. Cruden and R. Fell (editors). A.A. Balkema, Rotterdam, Netherlands, pp. 51–109.

Ferguson, S.A. 2000. Spatial and temporal variability of rain on snow. *In* Proc. ISSW 2000, International Snow Science Workshop, Big Sky, Mont., pp. 178–183.

Fitzharris, B.B. and I.F. Owens 1980. Avalanche atlas of the Milford Road: an assessment of the hazard to traffic. N.Z. Mountain Safety Council, Wellington, N.Z. Avalanche Committee Report 4.

Fredston, J. and D. Fesler. 1994 Snow sense: a guide to evaluating snow avalanche hazard. Alaska Mountain Safety Centre, Inc., Anchorage, Alaska.

Frey, W. and B. Salm. 1990. Snow properties and movements in forests of different climatic regions. *In* Proc. IUFRO, XIX World Congress, Montreal, Que. 1990. Div. 1, Vol. 1, pp. 328–339.

Furdada, G., G. Marti, P. Oller, M. Mases, and J.M. Vilaplana. 1995. Avalanche mapping and related GIS. Applications in the Catalan Pyrenees. Surveys in Geophysics. 16:681–693.

Gassner, M., H.-J. Etter, K. Birkeland, and T. Leonard. 2000. NXD2000: an improved avalanche forecasting program based on the nearest neighbour method. *In* Proc. ISSW 2000, International Snow Science Workshop, Big Sky, Mont., pp. 52–59.

Gerath, R., O. Hungr, and D. VanDine. 1996. Terrain stability mapping in British Columbia. Earth Science Task Force of the British Columbia Resources Inventory Committee, Victoria, B.C.

Giraud, G. 1992. MEPRA: an expert system for avalanche risk forecasting. *In* Proc. ISSW '92, International Snow Science Workshop, Breckenridge, Colo., pp. 97–105.

Golding, D.L. 1982. Snow accumulation in openings and adjacent forest. Can. Hydrol. Symp., Associate Committee on Hydrology, National Research Council of Canada, Fredericton, N.B., pp. 91–112.

Government of British Columbia. 1995. The West Kootenay–Boundary Land Use Plan. Victoria, B.C.

Greene, E.M., G.E. Liston, and R. A. Pielke. 1999. Simulation of above treeline snowdrift formation using a numerical snow-transport model, Cold Regions Science and Technology 30:135–144.

Gruber, U. and P. Bartelt. 2000. Study of the 1999 avalanches in Obergoms Valley, Switzerland, with respect to avalanche hazard mapping. *In* Proc. ISSW 2000, International Snow Science Workshop. Big Sky, Mont., pp. 495–500.

Gubler, H. and J. Rychetnik. 1990. Effects of forests near timberline on avalanche formation. *In* Proc. ISSW '90, International Snow Science Workshop, Bigfork, Mont., pp. 73–92.

Gumbel, E.J. 1958. Statistic of extremes. Columbia Univ. Press, New York, N.Y.

Hageli, P. and D.M. McClung. 2000. A new perspective on computer aided avalanche forecasting: scale and scale issues. *In* Proc. ISSW 2000, International Snow Science Workshop, Big Sky, Mont., pp. 66–73.

Hammond, C.J., D. Hall, S. Miller, and P. Swetik. 1992. Level I stability analysis (LISA). Vers. 2. USDA For. Serv., Intermountain Res. Stn., Ogden, Utah. Gen. Tech. Rep. INT-285.

Harbitz, C.B., D. Issler, and C. Keylock. 1998. Conclusions from a recent survey of avalanche computational models. *In* Twenty-five years of snow avalanche research. Norwegian Geotechnical Institute. NGI Pub. 203:128–139.

Heatherington, E.D. 1987. The importance of forests in the hydrologic regime. Can. Bull. Fish. Aquatic Sci. 215:170–211.

Hestnes, E., S. Bakkehoi, and F. Sandersen. 1994. Weather and snowpack conditions essential to slushflow release and downslope propagation. *In* Proc. ISSW '94, International Snow Science Workshop, Snowbird, Utah, pp. 40–57.

Hétu, B. 1990. Evolution récente d'un talus d'éboulis en millieu forestier, Gaspésie, Québec. Géographie Physique et Quaternarie 44(2):199–215.

Heumader. J. 1999. Forest-technical measures to support artificial and natural regeneration of steep-slope mountain forests. *In* Proc. IUFRO workshop. Structure of mountain forests: assessment, impacts, management, modelling. Swiss Federal Institute for Forest, Snow and Landscape Research, Davos, Switzerland.

Holler, P. 1994. Avalanche warning and hazard zoning in Austria: some new aspects. *In* Proc. ISSW '94, International Snow Science Workshop, Snowbird, Utah, pp. 459–463.

Howes, D.E. and E. Kenk. 1998. Terrain classification system for British Columbia. B.C. Min. Environ., Lands and Parks, Victoria, B.C. Manual 10. Vers. 2.

Hungr, O. 1997. Some methods for landslide hazard intensity mapping. *In* Proc. Workshop on Landslide Risk Assessment, Honolulu, Hawaii. D.M. Cruden and R. Fell (editors). A.A. Balkema, Rotterdam, Netherlands, pp. 215–26.

Internationale Kommission für Alpines Rettungswesen (IKAR). 1998. ICAR test-avalanche beacons. International Commission for Alpine Rescue. Tyrol, Austria.

Ja...eson, B. 1995. Avalanche prediction for persistent snow slabs. PhD thesis. Univ. Calgary, Calgary, Alta.

_____. 1997. Backcountry avalanche awareness. Can. Avalanche Assoc., Revelstoke, B.C.

Jamieson, B. and T. Geldsetzer. 1996. Avalanche accidents in Canada: Vol 4. Can. Avalanche Assoc. Revelstoke, B.C.

Jamieson, B. and C. Johnston 1999. Snowpack factors associated with strength changes of buried surface hoar layers. Cold Regions Science and Technol. 30:19–34.

Jamieson, B. and J. Schweizer. 2000. Texture and strength changes of buried surface hoar layers with implications for dry snow-slab avalanche release. J. Glaciol. 46(152):151–160.

Jamieson, B. and D. Svederus. 1997. Sledding in avalanche terrain: reducing the risk. Can. Avalanche Assoc. Revelstoke, B.C.

Jenkins, M.J. 1994. Using vegetative analysis to determine the extent and frequency of avalanches in Little Cottonwood Canyon, Utah. *In* Proc. ISSW '94, International Snow Science Workshop, Snowbird, Utah, pp. 91–103.

Johnson, B., B. Jamieson, and C.D. Johnston. 2000. Field data and theory for human-triggered "whumpfs" and remote avalanches. *In* Proc. ISSW 2000, International Snow Science Workshop, Big Sky, Mont., pp. 208–214.

Johnson, E.A., L. Hogg, and C.S. Carlson. 1985. Snow avalanche frequency and velocity for the Kananaskis Valley in the Canadian Rockies. Cold Regions Science and Technol. 10:141–151.

Johnson, J.B. 2000. Bigger may be better: determining the equivalent explosive effect for different explosives. Can. Avalanche Assoc. Avalanche News 61:12–18.

Joint Practice Board (JPB). 2002. Snow avalanche assessments in the forestry sector: skill sets for QRPs. Co-published by the Assoc. of B.C. Professional Foresters and Assoc. of Professional Engineers and Geoscientists of B.C. Innovation. April 2002, pp. 22–23.

Jomelli, V. and B. Francou. 2000. Comparing the characteristics of rockfall talus and snow avalanche landforms in an alpine environment using a new methodological approach: Massif des Ecrins, French Alps. Geomorphology 35:181–192.

Joseph, S.W. 1994. Expert systems: new ammunition for avalanche forecasting in B.C. B.C. Professional Engineer. Dec., pp. 5–8.

Keey, R. 1998. Australia/New Zealand Risk Management Standard A/N.Z.4360:1995. Owning the future: integrated risk management in practice. D. Elms (editor). Centre for Advanced Engineering. Christchurch, N.Z., pp. 91–97.

_____. 2000. Management of engineering risk. Centre for Advanced Engineering - Institution of Professional Engineers, Wellington, N.Z.

Kelly, D., J. Bay, and R. Stevens. 1997. Avalanche likelihood mapping. TFL 56 (1:20 000). Prepared for B.C. Min. For., Revelstoke, B.C.

Keylock, C.J. and M. Barbolini. 2001. Snow avalanche impact pressure: vulnerability relations for use in risk assessment. Can. Geotech. J. 38(2):227–238.

Keylock, C.J., D.M. McClung, and M.M. Magnusson. 1999. Avalanche risk mapping by simulation. J. Glaciol. 45(150):303–314.

Kootenay Inter-Agency Management Committee. 1996. The Kootenay–Boundary Land Use Plan: implementation strategy. Government of British Columbia, Victoria, B.C.

LaChapelle, E.R. 1966. Encounter probabilities for avalanche damage. USDA For. Serv., Alta Avalanche Study Centre, Wasatch National Forest, Alta, Utah. Misc. Rep. 10.

_____. 1980. The fundamental process in conventional avalanche forecasting. J. Glaciol. 26(94):75–84.

Lambert, R. 1992. The representation foreseeable natural risks: a contribution to a new cartography of avalanches. Theor. Appl. Clim. 45:83–88.

_____. 2000. Retrospective feedback on avalanches of February 1999 in the European Alps. *In* Proc. ISSW 2000, International Snow Science Workshop, Big Sky, Mont., pp. 501–508.

Lied K, F. Sandersen, and R. Toppe 1989. Snow avalanche maps for use by the Norwegian Army. Ann. Glaciol. 13:164–169.

Lied, K. and R. Toppe. 1989. Calculation of maximum snow avalanche runout distance by use of digital terrain models. Ann. Glaciol. 13:170–175.

Lister, D.R., Z. Bige, and J.B. Johnson. 1986. Coquihalla Highway natural hazards and forestry operations. Report of the Joint Task Group. B.C. Min. Transportation and Highways, Victoria, B.C.

McClung, D.M. 1989. Extreme avalanche runout: data from four mountain ranges. Ann. Glaciol. 13:180–184.

_____. 1990. A model for scaling avalanche speeds. J. Glaciol. 36(123):189–198.

_____. 1999. The encounter probability for mountain slope hazards. Can. Geotech. J. 36(6):1195–1196.

_____. 2000. Extreme avalanche runout in space and time. Can. Geotech. J. 37(1):161–170.

_____. 2001a. Characteristics of terrain, snow supply and forest cover for avalanche initiation caused by logging. Ann. Glaciol. 32:223–229.

_____. 2001b. Extreme avalanche runout: a comparison of empirical models. Can. Geotech. J. 38(1):1254–1265.

_____. 2001c. Superelevation of flowing avalanches around curves in channel bends. J. Geophys. Res. 106(B8):16,489–16,498.

_____. [2002]. Magnitude and frequency of avalanches in relation to terrain and forest cover variables. Arctic, Antarctic and Alpine Research. In prep.

McClung, D.M., B. Jamieson, C. Stethem, and P.A. Schaerer (editors). 2002. Guidelines and standards for avalanche risk and hazard mapping for Canada. Canadian Avalanche Association, Revelstoke, B.C., National Search and Rescue Secretariat, Ottawa, Ont.

McClung, D.M. and A.I. Mears. 1991. Extreme value prediction of snow avalanche runout. Cold Reg. Sci. Technol. 19:163–175.

_____. 1995. Dry-flowing avalanche run-up and runout speeds. J. Glaciol. 41(138):359–372.

McClung, D.M., A.I. Mears, and P.A. Schaerer. 1989. Extreme avalanche runout: data from four mountain ranges. Ann. Glaciol. 13:180–184.

McClung, D.M. and F.P.D. Navin. [2002]. Linear risk maps for snow avalanche hazards on British Columbia highways. Civil Engineering and Environmental Systems. In press.

McClung, D.M. and P.A. Schaerer. 1981. Snow avalanche size classification. *In* Proc. Avalanche Workshop, Associate Committee on Geotechnical Research. National Research Council of Canada, Ottawa, Ont. Tech. Memo. 133. pp. 12–27.

_____. 1993. The avalanche handbook. The Mountaineers, Seattle, Wash.

McClung, D.M. and J. Schweizer. 1999. Skier triggering, snow temperature and the stability index for dry slab avalanche initiation. J. Glaciol. 45(150):190–200.

McClung, D.M. and K. Stitzinger. [2002]. Risk-based decisions for logging in potential avalanche terrain. In prep.

McClung, D.M. and J. Tweedy. 1994. Numerical avalanche prediction: Kootenay Pass, British Columbia, Canada. J. Glaciol. 40(135):350–358.

McClung, D.M., S. Walker, and W. Golley. 1994. Characteristics of snow gliding on rocks. Ann. Glaciol. 19:97–103.

Margreth, S. 1996. Experience in the use and the effectiveness of permanent supporting structures in Switzerland. *In* Proc. ISSW '96, International Snow Science Workshop, Banff, Alta., pp. 233–238.

_____. 2000. Effectiveness of long term avalanche defence measures in winter 1999 in Switzerland. *In* Proc. ISSW 2000, International Snow Science Workshop, Big Sky, Mont., pp. 501–508.

Martinelli, M., Jr. 1974. Snow avalanche sites, identification and evaluation. U.S. Dep. Agric. Inf. Bull. 360.

Mears, A.I. 1992. Snow avalanche hazard analysis for land use planning. Colo. Geol. Surv., Denver, Colo. Bull. 49.

Morgan, G.C. 1997. A regulatory perspective to slope hazards and associated risks to life. *In* Proc. Workshop on Landslide Risk Assessment, Honolulu, Hawaii. D.M. Cruden and R. Fell (editors). A.A. Balkema, Rotterdam, Netherlands, pp. 285–295.

Motta, R., J.C. Haudemand, and A. Collatin. 1999. Protection forests of the Aosta Valley: stability and silviculture. *In* Proc. IUFRO workshop. Structure of mountain forests: assessment, impacts, management, modelling. Swiss Federal Institute for Forest, Snow and Landscape Research, Davos, Switzerland.

Mowat, G. and R. Ramcharita. 1999. A review of grizzly bear habitat use and habitat management options for the Kootenay Region of British Columbia. Timberland Consultants. Report to B.C. Min. Environ., Lands and Parks. Nelson, B.C.

Nixon, D.J. and D.M. McClung. 1993. Snow avalanche runout from two Canadian mountain ranges. Ann. Glaciol. 18:1–6.

Oke, T.R. 1983. Boundary layer climates. Methuen, London, U.K. and New York, N.Y.

Perla, R. 1977. Slab avalanche measurements. Can. Geotech. J. 14(2):206–213.

Perla, R., T.T. Cheng, and D.M. McClung. 1980. A two parameter model of snow avalanche motion. J. Glaciol. 26(94):197–207.

Perla, R. and M. Martinelli Jr. 1976. Avalanche handbook. USDA For. Serv. Rocky Mountains For. Range Exp. Stn., Fort Collins, Colo., U.S. Dep. Agric. Handb. 489.

Press, S. J. 1989. Bayesian statistics: principles, models, and applications. Wiley, New York, N.Y.

Quinn, M.S. and J. Phillips. 2000. Avalanche paths in TFL14: inventory, description, classification and management. Report to Crestbrook Forest Industries Inc. FRBC Project: KB96-204-IN.

Roeger, C., D.M. McClung, R. Stull, J. Hacker, and H. Modzelewski. 2000. Verification of high-resolution numerical weather forecasting models with regard to avalanche forecasting. *In* Proc. ISSW 2000, International Snow Science Workshop, Big Sky, Mont., pp. 74–77.

Rollerson, T.P., L. Zhongyou, and S. Jenvey. 2000. Combining induced hazard mapping with natural hazard mapping. Aspect: the DEGIFS Newsletter 5(1):9–11.

Ryder, J.M. 2002. A user's guide to terrain stability mapping in British Columbia. Assoc. of Professional Engineers and Geoscientists of B.C. Division of Engineers and Geoscientists in the Forest Sector Terrain Stability Mapping Task Force. Burnaby, B.C. www.degifs.com/resources.php3?category=browsecategories&item=95

Saeki, M., R. Wakabayashi, S. Watanabe, Y. Ohzeki, and S. Niwano. 1981. Forest cutting and avalanches on heavy snow slopes. Seppyo 43(1):15–20.

Salm, B. 1978. Snow forces on forest plants. *In* Mountain forests and avalanches. IUFRO, SFISAR, Davos, Switzerland, pp. 157–181.

Salm, B. and H. Gubler. 1985. Measurement and analysis of motion of dense flow avalanches. Ann. Glaciol. 6:26–34.

Schaefer, D.G. 1978. Climate. *In* The soil landscapes of British Columbia. K.W. Valentine, P.N. Sprout, T. E. Baker, and L. M. Lavkulich. (editors). Resour. Anal. Br., B.C. Min. Environ., Victoria, B.C.

Schaerer, P.A. 1972. Terrain and vegetation of snow avalanche sites at Rogers Pass, British Columbia. Mountain geomorphology: geomorphological processes in the Canadian Cordillera. B.C. Geog. Ser. 14:215–222.

_____. 1977. Analysis of snow avalanche terrain. Can. Geotech. J. 14(3):281–287.

_____. 1989. The avalanche hazard index. Ann. Glaciol. 13:241–247.

_____. 1991. Suggestions for snow research. *In* Proc. Workshop, Centre for Snow Science, Alta, Utah.

Schweizer, J. and P. Fohn. 1994. Two expert systems to forecast avalanche hazard for a given region. *In* Proc. ISSW '94, International Snow Science Workshop, Snowbird, Utah, pp. 295–310.

Sidle, R.C. 1991. A conceptual model of the effects of timber harvesting on slope stability. J. Environ. Quality 20(1):43–52.

Smith, K. 1992. Environmental hazards: assessing risk and reducing disaster. Routledge, London, U.K.

Smith, M.J. and D.M. McClung. 1995. Avalanche frequency at Rogers Pass, British Columbia, Canada. J. Glaciol. 43(143):165–171.

_____. 1997. Characteristics and prediction of high frequency avalanche runout. Arc. Alp. Res. 29(3):352–357.

Stathers, R.J., T.P. Rollerson, and S.J. Mitchell. 1994. Windthrow handbook for British Columbia forests. Res. Br., B.C. Min. For., Victoria, B.C. Work. Pap. No. 01/1994.

Stedinger, J.R., R.M. Vovel, and E. Foufoula-Georgion. 1993. Frequency analysis of extreme events. *In* Handbook of hydrology. D.R. Maidment (editor). McGraw Hill, New York, N.Y.

Stethem, C. and P.A. Schaerer. 1979. Avalanche accidents in Canada. National Research Council of Canada, Ottawa, Ont. DBR. Paper 834:57–59.

Stethem, C., P.A. Schaerer, and B. Jamieson. 1996. Snow avalanche hazard in forest management. Report to B.C. Min. For., Integrated Resources Policy Branch, Victoria, B.C.

Stevens, V. 1995. Wildlife diversity in British Columbia: distribution and habitat use of amphibians, reptiles, birds, and mammals in biogeoclimatic zones. Res. Br., B.C. Min. For., Victoria, B.C. Work. Pap.04/1995.

Stitzinger, K. 2001. Snow avalanche risk and decision support on clearcut harvested terrain. MSc thesis, Geog. Dep., Univ. B.C., Vancouver, B.C.

Stitzinger, K., P. Weisinger, and D. McClung. 2001. Avalanche activity and interaction with harvested terrain: terrain analysis and decision support for risk management. ISSW 2000, International Snow Science Workshop, Big Sky, Mont., pp. 458–461.

Stöckli, V. 1999. Significance of snow for the regeneration of a spruce forest: results from the Lusiwald-trial. *In* Structure of mountain forests: assessment, impacts, management, modelling. Proc. IUFRO workshop. Swiss Federal Institute for Forest, Snow and Landscape Research, Davos, Switzerland.

Strahlendorf, P. 1998. Supervisory due diligence: doomed if you don't. OHS Canada. Jan./Feb. pp. 36–42.

Swiss Federal Institute for Snow and Avalanche Research (SFISAR). 1990. Guidelines for avalanche protection utilizing structures in the starting zone. (Original title: Richtlinien für den Lawinenverbau im Anbruchgebiet.) Davos, Switzerland.

Tanner, B.D. 1990. Automated weather stations. Remote Sensing Reviews 5(1):73–98.

Taylor, B., L. Kremsater, and R. Ellis. 1997. Adaptive management of forests in British Columbia. B.C. Min. For., Research Program. Forestry Division Services Branch, Victoria, B.C.

Thrower, J.S., A.F. Nussbaum, and C.M. Di Lucca. 1991. Site index curves and tables for British Columbia: interior species. B.C. Min. For., Res. Br. Forestry Productivity and Decision Support Section. Victoria, B.C. Land Manage. Handb. Field Guide Insert 6.

Vink, S.G. 1992. Risk in geotechnical practice. Geotechnique and natural hazards. *In* Proc. Geohazards '92 Symp., Vancouver, B.C., May 6–12, Canadian Geotechnical Society, pp. 41–62.

Watson, A., C.J. Phillips, and M. Marden. 1999. Root strength, growth and rates of decay: root reinforcement changes of two tree species and their contribution to slope stability. Plant and Soil, 217(1):39–49.

Watt, W.E, K.W. Lathem, C.R. Neill, T.L. Richards, and J. Rousselle (editors). 1989. Hydrology of floods in Canada: a guide to planning and design. National Research Council of Canada, Ottawa, Ont.

Weir, P.L. 1998. Avalanche risk management: the Milford Road. *In* Owning the future, integrated risk management in practice. D. Elms (editor). Centre for Advanced Engineering, Wellington, N.Z., pp. 275–292.

Weir, P.L. and A. Auer, Jr. 1995. Forecasting avalanche hazards on the Milford Road, the role of meso-scale weather forecasts. *In* N.Z. Hydrological and Meteorological Society Symp., Christchurch, N.Z.

Weir, P.L. and W. Carran. 1997. Helicopter mounted rescue beacons: a high speed, low exposure avalanche search procedure. Can. Avalanche Assoc., Revelstoke, B.C. Avalanche News 47:11.

Weir, P.L. and D.M. McClung. 1994. Computer based artificial intelligence as an aid to B.C. MoTH's avalanche forecasters. Can. Avalanche Assoc., Revelstoke, B.C. Avalanche News 42:1–2 and 43:2–4.

Weir, P.L. and I.F. Owens. 1980. Snowpack structure at Mt. Hutt in 1979. N.Z. J. Sci. 24(1):95–102.

Wilkinson, J.M.T. and R.J. Fannin. 1997. A probabilistic technique for terrain stability assessment of open slopes in British Columbia. *In* Proc. 11th Vancouver Geotechnical Society Symp. Forestry Geotechnique and Resource Engineering. BiTech, Vancouver, B.C. pp. 17–30.

Wu, T.H., W.H. Tang, and H.H. Einstein. 1996. Landslide hazard and risk assessment. *In* Landslides investigation and mitigation. A.K. Turner and R.L. Shuster (editors). Transportation Research Board, U.S. National Research Council. Spec. Rep. 247:106–118.

World Meteorological Organisation (WMO). 1983. Guide to meteorological instruments and methods of observation. No. 8. 5th ed., Geneva, Switzerland.

PHOTO CREDITS

Joe Alcock
District Earth Scientist
B.C. Ministry of Forests
Golden, British Columbia, Canada

Fig. 73, p. 49

Bruce Allen
District Avalanche Technician
B.C. Ministry of Transportation
Revelstoke, British Columbia
Canada

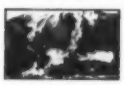


Fig. 18, p. 16

Fig. 21, p. 18

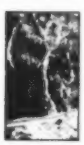


Fig. 20, p. 23

Fig. 135, p. 121

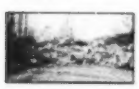


Fig. 138, p. 125

Applied Snow and Avalanche Research Group
Department of Civil Engineering
University of Calgary
Calgary, Alberta, Canada

Fig. 8b, p. 10

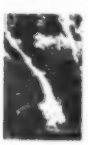
Fig. 118, p. 103

Fig. 119, p. 104

Fig. 120, p. 104

Frank Baumann
Baumann Engineering
Squamish, British Columbia
Canada

Fig. 39, p. 27



Back cover

Jim Bay
Mountain Light Tours
Revelstoke, British Columbia, Canada

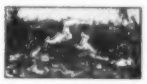


Fig. 3, p. 6

Fig. 6, p. 9

Fig. 17, p. 16

Fig. 11b, p. 13

Fig. 29, p. 23

Fig. 35, p. 27

Jim Bay *continued*

Fig. 48, p. 30

Fig. 105, p. 93

Fig. 144, p. 131

Fig. 145, p. 132

Fig. 146, p. 132

Fig. 148, p. 133

Fig. 149, p. 133

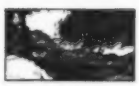


Fig. 150, p. 134

Fig. 151, p. 134

Dr. Karl Birkeland
Avalanche Scientist
U.S. Forest Service National
Avalanche Center
Boseman, Montana. USA

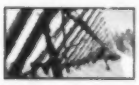


Fig. 68, p. 46

Fig. 141, p. 129

Fig. 142, p. 130

Fig. 143, p. 130

Mike Boissonneault
Senior Avalanche Officer
B.C. Ministry of Transportation
Victoria, British Columbia, Canada

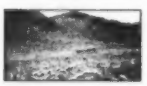


Fig. 1, p. 5

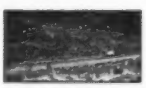


Fig. 26, p. 22

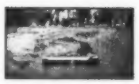


Fig. 61, p. 37

Dwain Boyer
Senior Floodplain Officer
Ministry of Water, Land, and
Air Protection, Nelson,
British Columbia, Canada

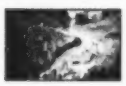


Fig. 60, p. 37

Wayne Carran
Works Civil Construction
Te Anau, New Zealand

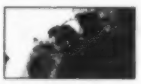


Fig. 131, p. 118

David Cupp
Photo Online Inc.
Hilliard, Ohio, USA

Fig. 66, p. 45

Alan Dennis
Scotland Avalanche Info Service
Whitehorse, NWT

Fig. 51, p. 32

Glynnis Hood
Ostapowich Engineering
Services Ltd., Saltspring Island,
British Columbia, Canada

Fig. 110a, p. 97

Fig. 110b, p. 97

Fig. 110c, p. 97

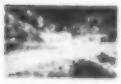


Fig. 110d, p. 97

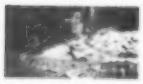


Fig. 111a, p. 97

Fig. 111b, p. 97

Fig. 111d, p. 97

Dr. Bruce Jamieson
Adjunct Professor, Department
of Geology and Geophysics
University of Calgary
Calgary, Alberta, Canada

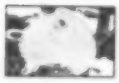


Fig. 28, p. 23

Fig. 32, p. 26

Fig. 104, p. 93

p. 101

Dr. Peter Jordan
Geomorphologist
B.C. Ministry of Forests
Nelson, British Columbia, Canada

Fig. 99, p. 88

Fig. 147, p. 133

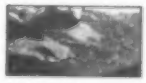


Fig. 153, p. 135

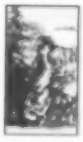
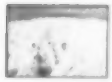


Fig. 154, p. 138


p. 129

Mack Karlstrom
Mountain Guide
Baldface Lodge, Nelson
British Columbia, Canada

p. 1

Peter Kimmel
Incline Research and Control Ltd.
Revelstoke, British Columbia, Canada

Fig. 15, p. 15

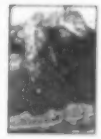


Fig. 27, p. 22

Fig. 33, p. 26

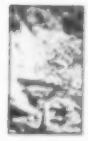


Fig. 37, p. 27

Fig. 40, p. 28

Peter Kimmel *continued*

Fig. 53, p. 34

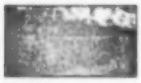


Fig. 71, p. 48

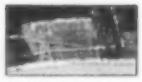


Fig. 74, p. 53

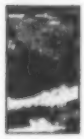


Fig. 82, p. 58

Fig. 100, p. 88

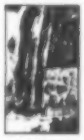


Fig. 106, p. 94

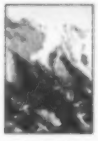


Fig. 112, p. 98

Fig. 113, p. 98

Fig. 121, p. 104

Fig. 132, p. 118

Hank Krawczyk
CMH Heli-Skiing
Banff, Alberta, Canada

Fig. 98, p. 88

Stefan Margreth
Swiss Federal Institute for Snow and Avalanche Research
Davos Village, Switzerland

Fig. 67a, p. 46

Fig. 67b, p. 46

Fig. 96, p. 85

Kevin Marr
Forestry consultant/Avalanche technician
Record Ridge Forestry
Slocan, British Columbia, Canada

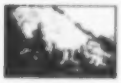


Fig. 80, p. 58

Lloyd Matheson
Te Anau, New Zealand

Fig. 133, p. 119

Dr. Dave McClung
Professor
Snow and Avalanche Science
University of British Columbia
Vancouver, British Columbia, Canada

Fig. 34, p. 27

Fig. 107, p. 95

D. McNulty Trust
New Zealand
(photographer unknown)

Fig. 52, p. 32

Mark Moore
Northwest Weather and
Avalanche Center
Seattle, Washington, USA

Fig. 57, p. 36

B.C. Ministry of Transportation
Victoria, British Columbia, Canada

Fig. 2, p. 5

p. 7

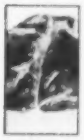


Fig. 14, p. 15

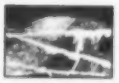


Fig. 114, p. 99

Fig. 134, p. 119

Fig. 140, p. 126

Doug Nicol
Road Geotechnical Engineer
B.C. Ministry of Forests
Nelson, British Columbia, Canada

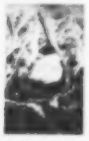


Fig. 108a, p. 96

Fig. 108b, p. 96

Dr. Ian Owens
University Proctor
University of Canterbury
Christchurch, New Zealand

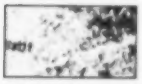


Fig. 137, p. 123

E. Pahaut
Météo - France/CNRM
Centre d'Etudes de la Neige
Grenoble, France

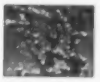


Fig. 4c, p. 7

© **Parks Canada**
Mount Revelstoke & Glacier
National Parks, Revelstoke
British Columbia, Canada

Cover/R.Greyall
615-288-0-094

Fig. 46, p. 29/J. Woods
615-0288-0-440

Dr. Michael Quinn
Assistant Professor, Environmental
Science and Planning
University of Calgary
Calgary, Alberta, Canada

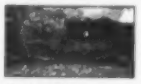


Fig. 62, p. 37

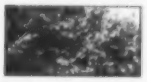


Fig. 63, p. 38

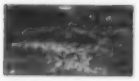


Fig. 64, p. 43

Fig. 65, p. 43

Lawrence Redfern
Forest Soils Analyst
Tembec Industries Inc.
Cranbrook, British Columbia
Canada

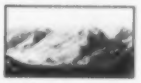


Fig.19, p. 16

Fig. 79, p. 57

Lawrence Redfern *continued*

Fig. 125, p. 109

Peter Schaerer
North Vancouver
British Columbia, Canada

Fig. 69, p. 47

p. 85

John Sebben
Cranbrook, British Columbia
Canada

Fig. 56, p. 34

Robin Siggers
Fernie, British Columbia
Canada

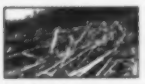
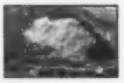


Fig. 54, p. 34

Chris Stethem
Chris Stethem & Associates
Snow Safety Services
Canmore, Alberta, Canada



P. 45

Dave Toews
Nelson, British Columbia
Canada

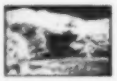


Fig. 109, p. 96

Dr. Hiroshi Uyeda
Strategic Planning Department
National Research Institute
Independent Administrative
Institute
Suyoshi, Nagaoka-shi
Niigata-ken, Japan

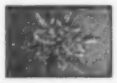


Fig. 4a, p. 7

Fig. 4b, p. 7

Peter Weir
Geoscience Solutions Group
www.geosolgroup.com

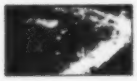


Fig. 8a, p. 10

Fig. 9, p. 12

Fig. 11a, p. 13

Fig. 36, p. 27

Fig. 38, p. 27

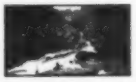


Fig. 41, p. 28

Fig. 42, p. 28

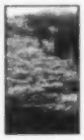


Fig. 43, p. 28

Fig. 47, p. 29

Fig. 50a, p. 31

Lawrence Redfern *continued*

Fig. 50b, p. 31

Fig. 50c, p. 31

Fig. 55, p. 34

Fig. 59, p. 37

Fig. 81, p. 58

Fig. 83, p. 59

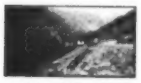


Fig. 115, p. 99

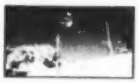


Fig. 126, p. 111

Fig. 127, p. 112

INDEX

accidents 5, 19, 56, 135
avalanche atlas 75, 76
avalanche bulletins 127–128, 156
avalanche classification 11–12
avalanche control 114–119, 137
  active 114
  passive 114
avalanche debris, removal 121, 126
avalanche defence structures 46
  static defences 45
avalanche density 29–30
avalanche frequency 21, 22, 23
avalanche path 14
  documentation 75
  ecology 37–44
  runout zone 14, 16, 23, 27, 28
  start zone 14, 15, 32, 45–46, 137, 139
  track 14, 15
Avalanche Path Management Zones 43
avalanche prediction
  classes 102
  expert systems 108
  forecasting systems 108
  model 101
avalanche probability 24–25
  geomorphic indicators 26
avalanche rescue 122–127
  alternative rescue systems 126
  equipment 152–153
  helicopter search 125
  procedures 146
  rescue caches 126–127
  rescue exercises 127
  rescue transceivers 122–125
  response 149–150
  training 123
avalanche research 1–3
avalanche run-up 34
avalanche site identification
  form 158–159
avalanche size 18, 19, 21, 51
  classification 18, 19
avalanche speed 28–31
  air blast 30
  dry snow avalanches 28–30
  powder avalanches 30
  wet snow avalanches 31
avalanche susceptibility 49, 90
avalanche technicians 104, 115, 136
  training 3
avalanche training 3, 140, 146

biogeoclimatic ecological
  classification 37, 39–41, 42
Blue List 38, 42
bombing
  consequences 116–117, 121
  helicopter 117–118, 138
  objectives 115
  role of spotters 118
  timing 115, 116
bridges 95, 96, 97

case studies 129–141
  Airy Creek 132
  Coquihalla Highway 130
  Nagle Creek 133
  Ranch Ridge 131
  Salmo 131
  Southern Interior 135
  Wardance Slope 129
Class I data 101, 102
Class II data 101, 103–108
Class III data 101, 108–112
clearcut logging 6, 94
  See also harvest design
clearcuts 14, 15, 32, 62, 131, 132, 134, 135

debris flow 5, 27, 36, 132

elevations 8, 20, 21, 24
energy exchanges over snow
  spring 10–11
  winter 10

failure
  compressive 13
  shear 13
  slab 13
  tensile 13
forest cover, influence 11, 34
forest damage 5, 36, 49
forest regeneration 47–48, 57
freezing level 8

geomorphic indicators 27–28
glossary 163–166
graupel 7

habitat
  grizzly bear 38, 43, 98
  management 43
  protection guidelines 43, 96
  ungulates 43
  various species 39–41
harvest design 85–90
  block layout 90
  group selection 88
  patch cuts 88
  reserve areas 88
  slope length 86–87
  small patch 88
highways 21, 22, 57–62, 132
hydrological effects 35–37

impact pressure 82–84

loose snow avalanches 12

mapping, avalanche
  air photo interpretation 63–64
  environmentally sensitive areas 62
  field checking 64–66
  forest sector 73–74
  highways 70–71
  land use planning 66–74
  map scale 65
  map use and interpretation 74
  methods 60–62
  regional districts 71–72
  small-scale terrain features 64
  terrain stability 72–73

numerical avalanche forecasting 108
  See also avalanche prediction

observations, avalanche 101, 103
Occupational Health and
  Safety Regulations 4, 57, 143–144
online resources
  Canadian sites 154
  other sites 155
  U.S. sites 155

ownership of risk 56, 57
  See also risk

powder avalanche 31
protection forests 45–48, 130–131

rain-on-snow event 24, 31, 35
Red List 38, 42
references 167–181
rescue transceivers
  See avalanche rescue
return period 20, 24, 25, 81
rime 7, 10
risk
  analysis 20
  analysis matrix 50–51
  assessment 48–53, 55
  assessment checklist 160–161
  case studies 129–141
  classification 48–56
risk management 3–6
  ALARP framework 54
  forest planning 59, 62
  objectives 58
  responses 54
  responsibility 55
  strategies 53, 55
road layout 14, 95–100
rock fords 97
runout
  characteristics 33–34
  distance 80–81
runout prediction
  dynamics modelling 75–77
  probabilistic modelling 77–80
  statistical concepts 80–81

safety
  forest operations 56–57, 58, 145–153
  work procedures 140, 145–149
search and rescue
  plan procedures 150–151
signage 99, 131
silvicultural strategies 91–94
  increasing surface roughness 91–93
  modification of local
    scale climate 93–94
  retention of timbered margins 94
  species vulnerability 94

site index 47
skiing 94–95, 125
slab avalanches 12, 13–14, 31, 35, 133, 138
slab volume 14
slope
  angle 15, 16
  hazards 23
slushflow 27
snow
  accumulation 8–11, 20
  creep 17, 35
  glide 17, 18, 35
  metamorphism 8, 35
  physical properties 7
  seasonal snow 7–11
snow profile 105–106, 107
  interpretation 106
snow stability
  field test 104
  rating system 162
snow support structures 129–130
snowmobiles 13, 120, 125
snowpack 103–105
  snow stability test 104
stand density 47
stream crossing location 95–100
surface hoar 9, 10, 11, 24, 35, 131, 137

tarns 28
terrain stability field
  assessments 4, 53, 59, 88, 89
triggers 6
  remote 118
  timing 115–116

vegetative indicators 26–27

weather
  forecasting 112–114
  observations 108–112
  stations 111–112
wet snow avalanches 34
whumpf 13, 136
wildfire 47
wind exposure index 32
winter operations 119–121
  safety 119–120

Snow avalanches in recently harvested areas can damage new forest plantations, destroy downslope resources, and endanger public safety. This Land Management Handbook reviews snow avalanche science as it applies to forestry. It presents risk assessment methods for use in forestry planning, outlines harvest designs, and describes silviculture strategies to reduce the risk of snow avalanches. Approaches for managing avalanche risks to forest workers are also summarized. With an extensive bibliography and list of Internet resources, this publication will be a valuable reference for natural resource managers, recreation planners, land developers, and anyone who manages work sites in winter.

B.C. Government Publication Services, Publisher

www.publications.gov.bc.ca/

Please visit our web site for information on acquiring copies of this Land Management Handbook, and other publications published by the Government of British Columbia.

Printed in British Columbia
on recycled (10% post-consumer) paper

ISBN 0-7726-4881-6

9 780772 648815